SECTION III
FINDINGS

In this section, the progress already made in developing the main PEM fuel cell subsystem technologies and integrating subsystems into fuel cell power plants is reviewed, and the outlook for achieving major development goals is discussed. Beyond technical progress and cost considerations, other key factors that affect the ultimate prospects of fuel cell engines and vehicles are addressed: the prospective availability of fuels suitable for fuel cell electric vehicles; the capabilities and plans of the organizations engaged in the development of automotive fuel cell technology; and the commitments of the automobile industry to participate in this development and, eventually, employ fuel cell engines in their vehicles. The Panel undertook to collect and evaluate information on all of these factors.

III.1 STATUS OF AUTOMOTIVE PEM FUEL CELL TECHNOLOGY

A. CELL STACK AND COMPONENT TECHNOLOGY

Background

Until about 10 years ago, PEM fuel cells that operated on air and hydrogen — the most favorable fuel — delivered only a fraction of the current and power densities needed for a practical vehicle power source. At a typical power density of $0.1 W/cm^2$, the cost of the Nafion-type fuel cell membranes alone would exceed the cost of a combustion engine of comparable power. Even this modest performance was possible only if electrodes contained platinum electrocatalysts in amounts far above those economically feasible for automotive applications.

Equally important, the low power density of cells translated into a specific power of fuel cell stacks well below the levels required of automotive power sources. For example, at less than 0.1 kW per liter and per kg, the stack alone would occupy more than 500 liters and weigh more than 500 kg for a 50 kW fuel cell power plant.

During the 1980s, pioneering research supported by the Department of Energy at the Los Alamos and other national and university laboratories successfully applied electrocatalysis principles to the design and optimization of membrane-electrode “assemblies” (MEAs) — the heart of PEM fuel cells. The achievement of greatly enhanced electrode performance at far lower catalyst loadings enabled the subsequent development of high-performance, potentially low-cost PEM cell and stack technology by a number of industrial organizations. Beginning in the early 1990s, several development efforts began to focus on possible applications of PEM fuel cell technology to dispersed power generation and vehicle propulsion. The success of one of these development programs is illustrated in Figure III-1.

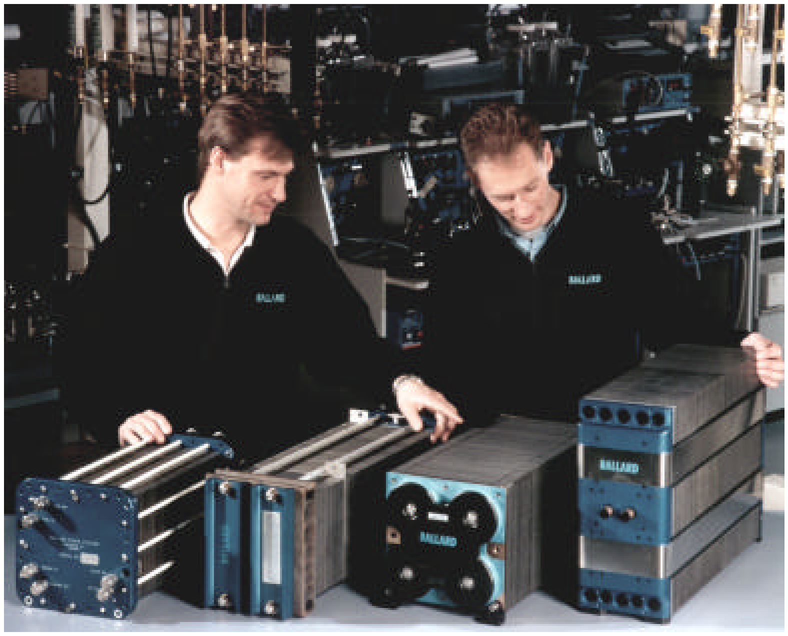

Figure III-1. Evolution of Ballard's PEM Fuel Cell Stack Technology

Ballard's 1991 PEM stack (on the far left in the figure) was capable of 5 kW peak power and had a volume of 59 liters; the 1997 stack (far right) can deliver 10 times more power (54 kW) from a volume of 54 liters.

Besides Ballard, a number of other organizations in Europe, Japan and the U.S. were involved in automotive PEM fuel cell stack development when the Panel began its inquiry. Leading automotive stack developers are listed in Table III-1; all of these were visited by the Panel between August and December 1997. Also included in the Table III-1 are several organizations active in the development of PEM cells and stacks primarily for mobile military or stationary commercial electric power generation, at least in the near term. The Panel visited these organizations as well, in the belief that elements of their technical progress might bear on the technology and prospects of automotive PEM fuel cells.

Table III-1. Commercial Organizations Developing PEM Fuel Cell Stack Technology

Corporation	Stack Production	Stack Manufacturing Techniques	Pre-pilot Stack Manufacturing	Full Size Development Stack (>25 kW)	Short Stack	Single Cell Technology	MEA Development / Manufacturer	Membrane Development/ Manufacturer	Catalyst Development	Separator Plate Development
Ballard	•	✓	✓	✓	✓	✓	✓			✓
Daimler Benz	•	✓	✓	✓						
General Motors				✓	✓	✓	✓			✓
Toyota				✓	✓	✓	✓			✓
Allied Signal					✓	✓	✓			✓
DeNora					✓	✓	✓			✓
Energy Partners					✓	✓				✓
Honda					✓	✓	✓			✓
H Power					✓	✓	✓			✓
IFC					✓	✓	✓			✓
Mitsubishi					✓	✓				✓
Nissan					✓(?)	✓		✓(?)		✓
Plug Power					✓	✓	✓			✓
Siemens					✓	✓	✓			✓

• Joint Ballard/Daimler Benz Program

Pilot production year — 2002

Full production year — 2004

As noted in Table III-1, these organizations are developing not only fuel cell and stack technology but membrane-electrode assemblies (MEAs) and separator plates, the two cell components on which cell and stack performance and cost depend in large measure. As stack development is progressing, the organizations developing automotive stack technology can be expected to focus increasingly on upscaling stacks to multi-kW sizes and developing the technologies and facilities for mass manufacturing of PEM fuel cell stacks and systems (see further below).

Development and fabrication of membranes and electrocatalysts typically are not addressed in the programs summarized in Table III-1 but are provided through customer-supplier or other business arrangements with more specialized organizations. A number of these organizations are listed in Table III-2.

Discussions with these organizations revealed that several of them also are developing MEA products to add value to the basic membrane. As a result, automotive stack and fuel cell power plant developers may be able to select MEAs for their stack development and/or manufacturing activities from several suppliers of high performance MEA products. The Panel's findings on the PEM technology status achieved by the organizations listed in Tables III-1 and III-2 are summarized here.

Technology Status: PEM Stack Developers

1. Allied Signal

Work on PEM fuel cell technology at Allied Signal began with a DOE contract for development of a 50 kW hydrogen-air stack intended for automotive applications. Allied's program has led to a stack technology with several novel features that were shown to the Panel during its 1997 visit. Foremost is the hexagonal shape of the cells and, therefore, of the stack footprint. Enclosing this stack in a cylindrical vessel and placing seals between the six stack edges and the inner wall of the vessel creates the six external manifolds for the inlets and opposed outlets of the three process streams (fuel, air, and coolant). This design results in a considerable simplification of stack manifolding and sealing. Another Allied stack feature is a metallic separator plate which allows dense stacking of cells.

The design is now being implemented in a DOE-funded program in which Allied will develop a 50 kW PEM fuel cell system capable of operating on processed methanol or gasoline. The performance goals for that system include 40% efficiency and a power density of 0.35 kW/liter. In parallel Allied is developing its cell and stack technology further by reducing the catalyst loading below 1 mg/cm^2 and improving the gas flow pattern in the cells through redesign of the gas flow fields in the separator plates. Manufacturing development of Allied's stack has not yet been initiated but its design

Table III-2. Organizations Developing PEM Fuel Cell Materials and Components

Corporation	Stack Manufacturing Techniques	Pre-pilot Stack Manufacturing	Full Size Development Stack (>25 kW)	Short Stack	Single Cell Technology	MEA Development/ Manufacturer	Membrane Development/ Manufacturer	Catalyst Development	Separator Plate Development
Gore						✓	✓		
Johnson Matthey						✓		✓	
3M						✓			
Asahi Chemical							✓		
DuPont							✓		
Hoechst							✓		

features should permit simplified and thus lower cost manufacturing of compact stacks, a major goal of every automotive PEM fuel cell program.

2. Ballard Power Systems

Over the past 10 years, Ballard has achieved recognition as a world leader in automotive PEM fuel cell technology, through overall size of its development effort (more than 200 people), performance of the technology (current stack power density more than 1 kW/liter), and capability for stack fabrication (more than 500 developmental stacks delivered to a wide variety of customers). The joint ventures established last year with Daimler-Benz and with Ford provide Ballard with the resources and capabilities to pursue extensive programs of technology improvement and cost reduction and, in parallel, to carry out engineering design and manufacturing development of cell and stack components, stack fabrication, and integration of stacks with fuel processors and other balance of power plant equipment. The technical basis for these extensive efforts is summarized here.

Cell/Stack Components. Ballard has established leading-edge technologies for all main functional components of PEM cells and stacks. In collaboration with Johnson Matthey, a world leader in noble metal production and application development, electrocatalysts were developed that give Ballard's MEAs high performance at low loadings (e.g., 0.2 mg catalyst per cm^2), good tolerance to CO (up to about 40 ppm, with concentration spikes up to 200 ppm) in the anode input gas, and acceptable endurance.

Ballard has evaluated the products from several of the major manufacturers of Nafion-type, fully fluorinated PE membranes. Concern about the high cost of commercially available membranes (about \$600 per m^2, equivalent to nearly \$100/kW) led Ballard to develop a proprietary, partially fluorinated PE material. At present, polymer resin is produced by Ballard in-house and then fabricated into "BAM" (Ballard Advanced Material) membranes by vendors.

Ballard's capacity for batch production of resin is sufficient to meet anticipated needs for several years. A continuous process is being developed for automated production of low-cost resin that should permit membrane costs to drop below \$50/m^2 in mass production. The endurance of BAM — an important issue for less than fully fluorinated membranes — is currently being tested under anticipated fuel cell operating conditions.

Using Nafion-type commercial or their own BAM membranes and platinum-based electrocatalysts, Ballard is producing high performance membrane-electrode assemblies in house, in the assumption that they will eventually manufacture MEAs on a large scale. However, Ballard still is open to the possibility of purchasing MEA components if specifications and price meet Ballard's criteria. Finally, several materials and fabrication options are currently being evaluated for eventual manufacturing of separator ("bipolar") plates of acceptable cost, for example about $1 per plate in volume production.

Stack technology. As shown in Figure III-2, the power density of Ballard's stacks has increased remarkably in a decade.

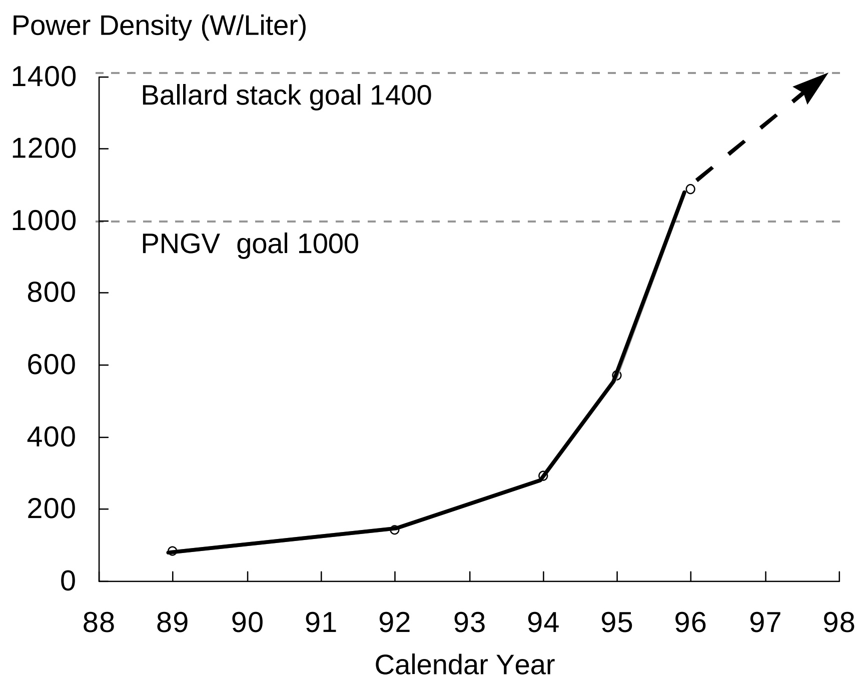

Figure III-2. Evolution of Ballard PEM Fuel Cell Stack Power Density

Current stack performance is over 1 kW/liter, twice the program goal established by PNGV only 3-4 years ago for the year 2004. Ballard's series "700" stacks, co-developed with Daimler Benz before their joint venture, are now being used in the NeCar 3 experimental fuel cell vehicle of Daimler-Benz (see below). The Ballard series "800" 50 kW stack is used in General Motors' program. In collaboration with Chrysler, this design is being optimized for operation on processed gasoline.

Ongoing efforts at Ballard are focusing on the series "900" 75 kW automotive fuel cell stack which is intended for volume production and application in the fuel cell vehicle Daimler-Benz plans to commercialize in 2004/5. In order to meet this schedule, the stack technology will have to be largely "frozen" by the end of 1998. Some of the stack design goals are shown in Table III-3:

Table III-3. Design Goals for Ballard's "900" Series Production Stack

Output power:	75kW @ 215 V stack voltage

Power density:	1.4 kW/liter
Life:	4000 hours
Freeze tolerance:	- 25°C

Ballard stacks are now being designed to be more freeze tolerant and to require less or no humidification of the reactant streams entering the stack.

Manufacturing Development. All parts of Ballard's cell and stack technology are being designed for high-volume, low-cost manufacturability. Important unit operations such as catalyst screen printing, MEA bonding and sealing have been validated on the small-scale pilot level. With assistance of Daimler-Benz manufacturing experts, manufacturing processes are being standardized, documented, and computerized, and engineers at the Ballard plant site work closely with manufacturing groups at DB to convert these techniques into manufacturing methods.

Ballard staff explained to the Panel how Ballard's stack production rate will increase as manufacturing processes are being developed and implemented. Once mature production at rates broadly comparable to those of modern IC engine plants are attained, stack production cost is projected to decline to $20-35/kW.

3. DeNora

DeNora is a world leader in the engineering and supply of cell technology for producing chlorine and caustic soda and for other electrochemical processes; all modern chlor-alkali plants use Nafion-type PE membranes as cell separators. DeNora also is a world leader in developing and producing dimensionally stable anodes. DSAs are highly corrosion resistant titanium electrodes that have special surface coatings to make them electrochemically active; they are used in a variety of industrial electrochemical processes.

DeNora's expertise in these areas was the basis for the company's decision around 1990 to initiate PEM fuel cell stack development. In 1996, DeNora purchased E-TEK, a small U.S. company that specializes in the development and supply of low catalyst-loading gas diffusion electrodes with high activity and good CO tolerance. With this base in PE membrane, DSA and noble metal-catalyzed electrodes, DeNora developed several generations of 5-10 kW PEM stacks with metallic separators. From the observations of the Panel, these stacks appear to be well designed and constructed; they have successfully passed Mil standard shock and vibration tests. The power density and specific power of DeNora's current stacks are about 1/3 kW per liter and per kg, respectively. Ongoing design improvements (such as thinner separator plates) will increase the performance of the next version to about 0.5 kW per liter and per kW.

A primary business interest of DeNora in PEM fuel cells is in the supply of complete hydrogen-air fuel cell systems for power generation using industrial "waste" hydrogen available on site as a byproduct of the chlor-alkali and other industrial processes. DeNora also is positioning itself to supply their PEM fuel cell stacks for other "high value" stationary power generation markets, partnering with fuel cell system and/or power plant suppliers.

In the transportation field, DeNora is interested in supplying their technology to higher-value niche markets for specialized work vehicles. The company sees itself primarily as a licensor rather than as a manufacturer of PEM fuel cell stack technology for the automobile mass market with its very severe cost and weight constraints for fuel cell engines. Nevertheless, DeNora has supplied PEM stacks for several fuel cell bus demonstrations funded by the European Community, and it is likely to provide stacks for future FCEV programs of the EC.

4. Energy Partners

Energy Partners (EP) established a position in PEM fuel cell technology by acquiring the Treadwell fuel cell technology and upscaling the Treadwell cell design to 11"x 11" size. EP's stacks feature a potentially low cost, molded separator plate. Using this technology, EP has built a number of multi-kW PEM hydrogen-air/oxygen stacks and sold them to research organizations worldwide. Other stacks were tried for powering several small, experimental fuel cell vehicles.

EP participated in the DOE/Ford automotive fuel cell stack development and evaluation program (1995-96) and delivered a 10 kW hydrogen-air PEM stack to Ford under that program. EP's stack used Gore's MEA but was not chosen in Ford's downselect. Subsequently, EP was awarded one of DOE's PRDAs to improve stack design. Excellent performance (up to 1 W/cm^2 @ 0.6 V) was achieved with subscale (150 cm^2) single cells operated on hydrogen at 30 psig; short stacks of such cells have delivered about 0.7 W @ 0.6 V. This stack technology is now being developed further under the current round of DOE contracts for 50kW stacks. In the first phase, EP will try to complete the development of a separator plate molded from a high-conductivity composite containing graphite, and it will fabricate a 10 kW proof-of-concept stack. In the second phase, EP is to construct a 50 kW stack as part of a PEM fuel cell power plant capable of operating on processed gasoline and/or methanol.

5. General Motors

GM is a principal participant in the "Partnership for the Next Generation of Vehicles" (PNGV). PNGV is a major industry-government program for the development of advanced technology to dramatically increase the efficiency and manufacturability of future automobiles (see also Section III.3.A below). During the last several years, the PNGV technical program undertook significant efforts to increase the power density and reduce the catalyst loadings of

PEM fuel cell stacks. PNGV's advances are now being integrated in the technology and manufacturing development activities of GM and other U.S. automobile manufacturers.

Independently and with little publicity, GM has carried forward R&D on PEM fuel cells. As shown in Table III-4, the GM stack technology has promising performance:

Table III-4. GM Development Stack Characteristics

Cell performance:	0.78v @ 200 ma/cm^2 0.65v @ 600 ma/cm^2
Membranes evaluated:	DuPont Nafion; Gore
MEA's evaluated:	GM, Gore
Separator candidates:	coated metal; conductive plastic
Test time:	200 (+) hrs

GM has completed the design of a 50 kW stack. This stack will incorporate the advances in electrocatalyst, MEA, and separator technologies currently being pursued within GM and in collaboration with several outside organizations. The need to reduce costs is the major driver in these efforts.

The GM program has initiated some manufacturing development work, but they have left open the options whether and which PEM fuel cell components and subsystems will be manufactured by GM, or indeed whether GM will ultimately elect to purchase rather than manufacture stacks. GM's corporate philosophy entails full understanding of all aspects of PEM fuel cell technology to permit informed future decisions on technology selection and partnering. With their fuel cell technology and skill base, engineering capabilities, and financial resources, GM will be able to move rapidly into engineering and manufacturing development of a competitive PEM stack technology.

6. Honda

The low-level fuel cell program initiated by Honda in 1989 was expanded significantly about 3 years ago, and further expansion is likely. PEM cell component and stack development comprise a major part of Honda's current program, with core technology R&D and feasibility assessment planned for another 2-3 years. The status of Honda's stack technology is summarized in Table III-5:

Table III-5. Honda's Development Stack Characteristics

Output power:	6.0 kW
Number of cells:	60
Power density:	approximately 0.2 kW/liter
Operating temperature:	75°C
Cell active area:	225 cm^2
Cell performance:	0.55v @ 1000 ma/cm^2

This good performance was achieved with MEAs developed by Honda which used Nafion membranes and modest loadings of commercial catalysts. The previous generation of cell technology showed very little degradation when tested for endurance up to 700 hours. The data above refer to hydrogen as fuel; cells have also been tested with simulated reformate containing up to 100 ppm of CO but data on performance and CO tolerance were not presented.

The Panel saw Honda's state-of-the-art laboratory-level facilities for MEA fabrication. At present, separator plates machined from commercial graphite composite are used in Honda's stacks. Manufacturing considerations are entering Honda's development efforts even at the core technology stage, but it has not yet been decided which components Honda will manufacture. Given sufficient progress, Honda expects to transition the program to systems integration, field testing and manufacturing development beginning in 2000.

7. H-Power

H-Power is a small company that has been active in phosphoric acid and PEM fuel cell development for 15 years. From an earlier emphasis on military applications, H-Power in the early 1990s expanded activities into PEM fuel cell technology for small stationary and portable power applications. Like DeNora, H-Power believes that PEM fuel cells are best suited for power applications where the value of high reliability and efficiency can justify fuel cell costs in the range of a few 100 $/kW to perhaps 1000 $/kW.

H-Power does have a unique metallic separator plate technology. Plates are made by diffusion bonding thin metal sheets cut in the appropriate patterns from sheet stock by a photo-etching technique. With this approach, H-Power can produce very thin separators with precisely defined flow fields and cooling passages, an important advantage for the fabrication of compact, high performance automotive PEM fuel cell stacks. Because it lends itself to automation, H-Power's technique should permit mass production of separators at relatively low cost, thereby meeting a key requirement for automotive applications. At this time, however, H-Power does not seem to have plans for transfer of their separator plate technology to other organizations.

8. International Fuel Cells (IFC)

While IFC's leadership in fuel cell development and fabrication dates back more than three decades, its involvement with PEM technology began in 1985 with acquisition of General Electrics' solid polymer electrolyte technology and business. Beginning in the late 1980s, IFC developed high reliability PEM fuel cells for military applications.

One product of these developments was a 20 kW fuel cell power system for an underwater vehicle. This stack utilized a carbon/graphite separator plate adopted from IFC's phosphoric acid technology. IFCs stack has a number of porous plates which transfer product water from cells to the cooling water stream by a "wicking" action. This feature simplifies water removal, achieves better membrane hydration and, according to IFC, improves cell performance at ambient pressure to levels that make pressurization unnecessary. This feature is now part of IFC's automotive PEM fuel cell stack technology.

Work on automotive PEM fuel cell technology began about 3 years ago with IFC's successful response to a Ford procurement of a hydrogen-air PEM stacks for testing and evaluation purposes under DOE's automotive fuel cell R&D program. Under the Phase II contract, IFC delivered a 50kW/250 Volt two-stack PEM fuel cell power plant. Operated at ambient-pressure air and hydrogen, this power plant has a power density of 0.55 kW/liter and an efficiency of 50% at rated power; at 10kW output (cruise power), efficiency is 60%.

Under a new $11 million DOE contract IFC will develop a fuel-flexible 50 kW power plant that can operate on gasoline, methanol or natural gas; system power density will be 0.25 kW/liter. This effort is now part of a larger UTC/IFC program to accelerate the development of gasoline-fueled PEM fuel cell power plants for automobiles, building on IFC's extensive background in fuel cell stack and fuel processing technologies.

9. Mitsubishi Electric

With funding from NEDO (see Section III.3. A), Mitsubishi is carrying out a PEM fuel cell R&D program aimed primarily at stationary power generation applications. However, several elements of the program have relevance for the automotive power source applications, including in particular Mitsubishi's development of a compact reformer which is discussed in the section on fuel processing (see III.1.B, below).

The Mitsubishi program includes a modest stack technology development effort that targets the NEDO cell power density goal of 0.3 kW/cm^2. This goal appears adequate for stationary applications that have less severe cost and volume constraints than the automotive application. Mitsubishi R&D has built an experimental stack with cells capable of 100mA/cm^2 at 0.7 Volt, equivalent to 0.07 kW/cm^2. This stack has internal humidification, liquid cooling, and it uses novel approaches to gas manifolding and flow field design. Testing has demonstrated ≥10,000 hours of endurance (an important goal for stationary applications) on hydrogen-air and stable performance on reformate with ≤10 ppm of CO.

It was pointed out to the Panel that Mitsubishi Heavy Industries also is developing PEM technology, but no decision has been made as to which Mitsubishi organization will eventually work with Mitsubishi Motors to develop automotive PEM fuel cells.

10. Nissan

At present, Nissan's PEM fuel cell program appears to be quite modest and, like Mitsubishi's program, is largely funded by NEDO. Nissan's activities have concentrated on estimating efficiencies and emissions of FCEVs and comparing them with gasoline-powered ICE vehicles, and evaluating two PEM stacks purchased from Ballard. A systematic program to develop PEM fuel cell components and subsystems does not exist at present but appears to be planned. Nissan staff mentioned cost goals of $20/kW for PEM automotive fuel cell stacks and $50/kW for complete fuel cell power plants.

Nissan's PEM fuel cell laboratory research started in 1996, with a focus on the direct methanol fuel cell because of its potential for reduced complexity. Nissan technical staff mentioned methanol crossover and the relatively low operating temperature limit of Nafion-type membranes as the most serious barriers to the development of practical direct methanol technology. Nissan is now engaged in an internally funded effort to develop a new membrane with higher resistance to methanol crossover and tolerance for operating temperatures above 150°C.

11. Plug Power

Plug Power (PP) is an organization established in 1997 by Mechanical Technologies Inc. (MTI) and Detroit Edison Development Co. as a partnership to commercialize the PEM fuel cell technology developed at MTI since the early 1990s. Plug Power has grown rapidly and now has more than 100 staff engaged in PEM fuel cell technology development. The primary business goal is to develop PEM fuel cell stack and system technology for stationary power generation in the residential sector, drawing on the energy technology system expertise of MTI and the electricity market knowledge of Detroit Edison.

PP also has become engaged in DOE's PEM fuel cell program, first as a supplier of a 10 kW stack under the Ford procurement, presently as one of the organizations selected to develop and deliver by the year 2000 a 50 kW PEM fuel cell power system capable of operating on processed gasoline. The fuel processor for that system is to be provided by ADL.

Currently, Plug Power is seeking strategic partners willing to invest in further development of Plug Power's technology and to provide some of the resources that will be required to manufacture and commercialize the technology.

12. Siemens

Siemens has a long and technically successful history in fuel cell development, and it continued to maintain a major corporate capability (currently about 100 technical staff) in fuel cells. About two-thirds of this staff is working on PEM fuel cell technology, with emphasis on the submarine power source ("battery extender") application.

Aiming for commercial applications, Siemens recently developed a simplified cell technology that appears amenable to low-cost mass production. The key cell performance characteristics and stack technology goals of this technology are summarized in Table III-6:

Table III-6. Siemens 1999 — Stack Technology Goals

Output power:	~ 6 kW
Stack power density:	0.4 kW/kg, 0.4 kW/l
Number of cells	30
Electrode area:	400 cm^2
Electrode catalyst loadings:	0.2 mg/cm^2
Cell performance:	0.7v @ 700 ma/cm^2

Siemens projects a cost of 200 DM/kW (approximately $110/kW) for a complete hydrogen-air system when manufactured in volume, e.g., 100,000 units per year. Because this cost is still too high for automotive applications, further development of the cell and stack technology and of appropriate manufacturing processes will be necessary.

Siemens expects to make a decision in 1999 whether to pursue automotive stack technology development and manufacturing beyond that year. At present, there appears to be some concern at Siemens about the extent to which automobile makers are willing to become engaged in alliances to develop PEM fuel cell engines. As a partner in a joint FCEV venture, Siemens could offer not only one of the largest fuel cell technology capabilities anywhere but, in addition, leading-edge electric drivetrain technology as well as the very large technical and financial resources of a world leader in a wide range of electric and electronic technologies.

13. Toyota

Toyota's fuel cell program began around 1990, with emphasis on development of hydrogen storage alloys and PEM stacks. The Toyota experimental fuel cell-battery hybrid EV, shown first in 1996, had a 15 kW hydrogen-air fuel cell, with hydrogen stored in form of a metal hydride. The characteristics of Toyota's stack technology are summarized in Table III-7:

Table III-7. Toyota's PEM Fuel Cell Stack Characteristics (for Hybrid EV)

Output Power:	15 kW @ 288 V
Number of cells:	400
Operating pressure:	0.5 bar
Operating temperature:	80°C
Stack weight:	120 kg
Stack volume:	100 liters (stack power density 0.15 kW/liter)

Cell performance:	0.6 V @ 900 ma/cm^2

This good performance was achieved with MEAs that were developed and fabricated in-house using Nafion membranes and low catalyst loadings (about 0.3 mg/cm^2); separator plates were machined from sintered carbon. Hydrogen at 0.5 bar was the primary fuel but testing with reformate showed cell/stack tolerance to 20 ppm of CO. Ten 25 kW stacks have now been built, but Toyota engineers stressed to the Panel that their stack technology is still developmental and that systematic manufacturing engineering and process development efforts must await breakthroughs in the prospective costs of key components including membranes/MEAs and the separator plate.

<u>Technology Status: Component Developers/Suppliers</u> (See Table III-2)

1. Asahi Chemical Co.

Asahi Chemical, a major chemicals manufacturer, is one of only three companies worldwide which produce the basic resin for manufacture of fully fluorinated polymer PE membranes; DuPont and Asahi Glass are the other two. Asahi Chemical also is a major producer of PE membranes — typically, multi-layer, fiber-reinforced structures — for industrial processes and the leading supplier of chlor-alkali cells, the largest current application of fluoropolymer PE membranes.

While the current price of these membranes is high, Asahi Chemical believes that it should be possible to reduce membrane costs by the order of magnitude required to make such membranes acceptable for automotive fuel cells. The key will be the development of a sufficiently large market (for example, 1 million m^2/year) to provide the needed economies of scale. The membrane cost question is being studied by Asahi Chemical staff, but they noted that costs are difficult to predict inasmuch as neither the specifications nor the markets of automotive fuel cell membranes are defined at this time.

Asahi Chemical is working on fluoropolymer membranes suitable for automotive applications. A relatively thin, reinforced experimental membrane is showing conductivity, strength and shape retention characteristics comparable to Nafion-type PEMs. These membranes are made from standard fluoropolymer resin and can be produced with existing machinery. With funding from NEDO's PEM fuel cell R&D program (see Section III.3.A below) Asahi Chemical is evaluating the durability of this membrane while the Asahi Glass is concentrating on increasing membrane performance.

2. DuPont

DuPont's NAFION® membrane, used since many years as ion-permeable separator in chlor-alkali and other industrial electrochemical cells, has become widely adopted in PEM fuel cells. Nafion offers very good ionic conductivity, outstanding chemical stability and high quality (uniformity and freedom from pinholes and other defects) — critically important characteristics for the fuel cell application.

The main drawback of Nafion is its high price. At least nine fluorochemical reaction processes are involved in synthesizing the perfluorinated, chemically functionalized ionomer resin from which membranes are made; some of these processes involve hazardous intermediates and thus require stringent controls to ensure safety. DuPont's Fayetteville site, visited by the Panel, is the world's largest integrated facility for producing these resins and a family of Nafion membrane products. Asahi Chemical and Asahi Glass in Japan are the only other industrial-scale producers of perfluorinated ionomer resins.

Because of the modest markets for Nafion-type membranes (currently about 100,000 m^2/year worldwide), resins and membranes are made in relatively small volume by chemical industry standards. Thus, the high cost of resin production plants and membrane manufacturing equipment must be recovered in the sale of a limited amount of product, resulting in rather high prices. However, DuPont has a strong business interest in serving the much larger markets for lower-cost membranes which are expected to develop if PEM fuel cells are eventually accepted on a large scale for stationary and portable power generation, and/or as vehicle power sources. Currently, there is some excess resin and membrane manufacturing capacity to serve emerging new markets; additional capacity can be created by eliminating bottlenecks in a few of DuPont's intermediate processes.

DuPont sees industrial processes and power generation as their first significant market opportunities, in part because these markets can tolerate higher costs of PEM technology and membranes. Accordingly, DuPont is now supplying ionomer resin and membranes to developers of water electrolyzers, portable power, and dispersed power generation. Currently, they have no plans for forward integration to include manufacturing of MEAs.

DuPont also is continuing to supply membranes and ionomer resin products to developers and potential manufacturers of MEAs and PEM fuel cells in the expectation that a mass market for these products will eventually develop. In support of that strategy, DuPont recently announced their future pricing schedule to serve a membrane market created by annual production of 150,000 PEM fuel cell engines and vehicles. At this volume (estimated by the Panel to be between 1 and 2 million m^2 per year, more than 10 times the current world market), membrane prices will drop to less than \$50/m^2, or less than \$10/kW for a high performance PEM stack. Two other factors could result in yet lower membrane costs per kW: the integration of ionomer resins or solutions — rather than the finished membrane — into MEA production, and/or (in the longer term) recycling and reuse of membranes in resin or membrane manufacture.

3. W. L. Gore Associates

Based on Gore's core competencies in fluoropolymer materials technology and membrane processing and backed by a strong management commitment, Gore established a team in 1994 to develop technology and a business in ionomer (ionically conducting polymer) membranes. This team rapidly developed GORE-SELECT®, a membrane micro-reinforced with teflon fibers and made from the same ionomer resin that is used to produce DuPont NAFION® membranes.

Gore's membranes have somewhat lower conductivity than Nafion but higher conductance because their good mechanical properties permit very thin membranes to be manufactured and used in fuel cells. MEAs made with these membranes have demonstrated impressive advances in PEM cell performance as shown in Figure III-3:

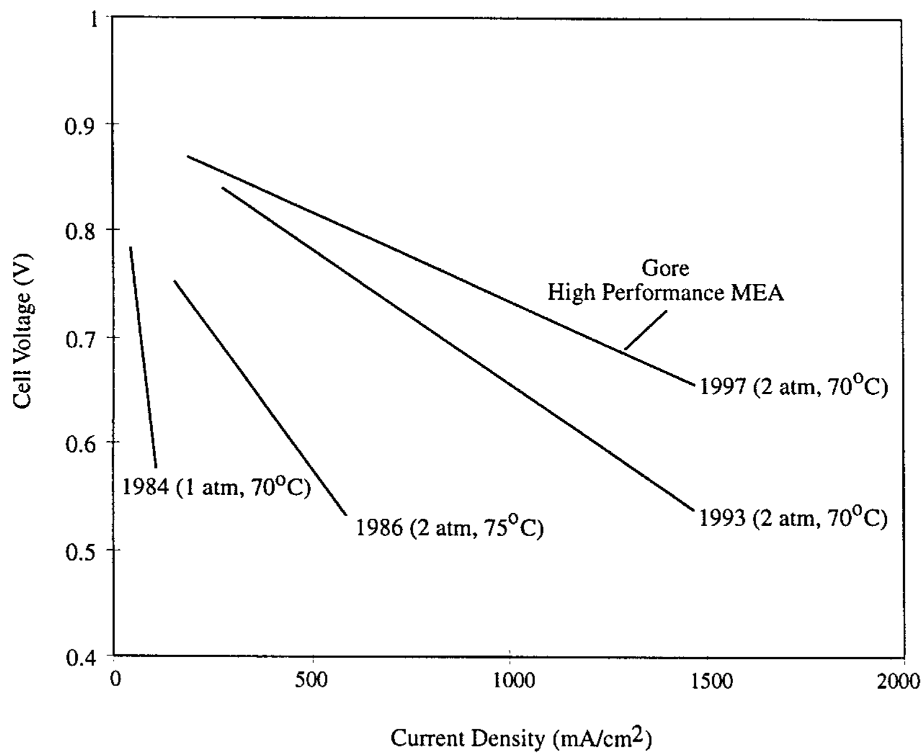

Figure III-3. Evolution of MEA Performance

Representative of today's high MEA performance is a current density of 1.4 A/cm^2 at 0.6 Volts per cell and a catalyst loading of 0.3 mg/cm^2. Gore claims that similar cell performance can be attained with much lower catalyst loadings. The gas diffusor/conductor material used in these cells also is made by Gore under the trade name CARBEL®.

In 1998, Gore is completing a manufacturing plant with the capacity to produce several hundred thousand m^2/year of Gore's fuel cell PEM in continuous rolls. This plant could supply membranes sufficient for production of approximately 40,000 automotive PEM stacks per year. Gore also plans to manufacture complete MEA structures by a continuous process, and the company plans to offer this material commercially under the trade name PRIMEA® in widths up to 1.8 meters beginning later in 1998. Gore intends to be a world leader in supplying MEAs, at a price that will capture fuel cell mass markets in power generation and/or transportation.

The Panel also discussed recycling of membranes with Gore staff. They have already demonstrated recovery of membranes from scrapped MEAs and believe that the chemical stability and ruggedness of Gore's membranes will permit recycling and reuse of membrane material and, if technically and economically justified, the membrane itself.

4. Hoechst

Hoechst is one of the world's largest producers of chemicals and polymer products, with extensive R&D capabilities and international business activities. Hoechst's Corporate Research & Technology (CR&T) has become engaged in PE membrane development believing that such membranes could turn into a major business opportunity if automotive PEM fuel cells can capture major markets.

Assuming that fluorinated PE membranes will be too expensive for automotive fuel cells and that their stability exceeds automotive requirements, Hoechst CR&T has developed a hydrocarbon-based PE membrane with a projected cost less than 10% of a Nafion-type membrane. MEAs based on this membrane have been fabricated at Hoechst and independently tested in laboratory cells, demonstrating sufficient stability up to at least 5000 hours. Hoechst can produce this membrane to order in pilot quantities and has supplied samples to major European PEM fuel cell developers for evaluation purposes.

Hoechst PEM product strategy is to combine a low-cost membrane with sufficiently high catalyst loadings (e.g., 0.25 mg/cm^2 for each side of the membrane) to create an MEA with some tolerance to the conditions (impurities; non-uniform flows, etc.) encountered by fuel cell stacks in practical applications. It was pointed out to Panel members that hydrocarbon-based membranes are more easily and safely disposed of than fluorinated membranes which can give off toxic chemicals when burned.

5. Johnson Matthey

Johnson Matthey is one of the world's leading developers and suppliers of noble metals and noble metal catalysts. The company has made a significant commitment to PEM fuel cell development, and it has adopted a long term plan to develop and supply fuel cell components containing noble metals, from the catalysts themselves to electrodes and complete MEAs.

In pursuit of that plan, Johnson Matthey established collaboration and business relationships with many leading fuel cell developers worldwide. A number of them now use Johnson Matthey's catalysts in their MEAs. In their own laboratories, Johnson Matthey is developing platinum and platinum alloy catalysts of higher electrochemical activity and improved electrode structures, with the goal of achieving cell power densities approaching 1 W/cm^2 with catalyst loadings around 0.35 mg/cm^2. This translates into a catalyst cost of approximately \$4-5/kW. With this level of catalyst performance, a low-cost membrane (e.g., \$30-50/m^2, corresponding to \$3-5/kW for 1 W/cm^2 cell performance) and large-scale automated production, a MEA cost of ≤\$15/kW should be achievable.

Johnson Matthey believes that it is well positioned to implement catalyst and MEA production on the levels required if and when PEM fuel cell technology is introduced into the automobile and/or power generation markets. Johnson Matthey's development of fuel processor technology, discussed below, is part of this positioning.

6. 3M

Although 3M initiated R&D on PEM fuel cell components as recently as 1995, it has successfully developed a new MEA technology based on their proprietary electrocatalyst support material. Use of this material and 3M's technique for depositing the catalyzed support on Nafion-type membranes result in MEAs of high performance (e.g., 0.55-0.65 W/cm^2 @ ≤2 bar) and excellent CO tolerance (e.g., ≥ 100 ppm) at low catalyst loadings (e.g., 0.25 mg/cm^2). To date, 3M's MEAs have been tested in about 300 cells with no performance degradation observed in the longest test of about 800 hours. Equally important, 3M has developed a process for continuous fabrication of complete 5-layer MEA structures as a "roll good." On the basis of MEA composition and performance, and with the expected low cost of the roll good manufacturing process, 3M projects MEA costs in the order of \$5-10/kW. 3M believes that this MEA cost should permit stack costs of \$ 20/kW, or \$1000 for a 50 kW automotive PEM stack.

A key assumption underlying 3M's MEA cost projection is a membrane cost of around \$20/m^2, about 1/30 of current prices for Nafion-type membranes. 3M believes that this cost should be achievable in mass production, e.g. ≥ 1 million m^2 per year.

3M estimates that it will take 2 years to develop their MEA technology to the point where an early commercial production line could be set up in an existing roll good production facility. Such facilities are used routinely by 3M to minimize investment — and thus keep the cost of a new product as low as possible — in the early stages of commercial introduction.

As a materials company, 3M wants to commercially produce MEAs but not stacks or entire fuel cell systems. 3M intends to establish alliances with stack manufacturers to ensure that stack manufacturing processes take full advantage of future availability of 3M's MEA as a continuous roll. A timing issue could develop if 3M's aggressive schedule for MEA process development and commercialization is not matched by the pace of a significant MEA demand (by 3M's prospective allies or by a broader market) over the next few years.

Summary and Outlook, PEM Stack Technology

The Panel's visits and discussions with leading developers and potential manufacturers of PEM fuel cell components and stacks made clear that the fundamental technical barriers to the development of automotive fuel cell stacks have been overcome by the advances achieved over the past 5-7 years. The large increases in the specific performance of PEM cells and stacks also have lowered the cost barriers to the point where future mass production may be able to meet the stringent cost goals for critical cell components and stacks intended for automotive applications. The most important advances in PEM automotive fuel cell stack technology, in the view of the Panel, are the following:

Electrocatalysts: A number of organizations have achieved specific anode and cathode catalyst performance in the range of 2000-5000 mA per mg of catalyst at practical cell voltages (e.g., 0.6-0.7 V). This high performance results from the increased activities and/or better utilization of platinum and platinum alloy electrocatalysts deposited on improved electrode structures made from carbon or novel support materials.

As a result of the greater than 10-fold increase of performance over the status only 4 years ago, electrocatalysts contribute now only about $4-10 per kW to stack costs — still significant but probably within the economically acceptable range. Although no catalyst performance projections were offered by developers, basic research has shown that high cell performance is possible with as little as 0.1mg of catalyst per cm^2 of electrode. This is another factor of 2-5 below current levels, a reasonable R&D goal for the highly competent catalyst suppliers and MEA developers now involved in PEM fuel cell component development.

At these very light loadings, electrocatalysts would contribute only $2-3 per kW to stack costs. There is, however, still some uncertainty whether such light electrocatalyst loadings will give anodes and cathodes sufficient endurance under the operating conditions encountered by fuel cell engines in practical use. Another important achievement is the increased anode electrocatalyst tolerance to carbon monoxide in the fuel processor output gas ("reformate"), from originally ≤10 ppm to around 100 ppm and possibly more now. Use of alloy anode catalysts and/or special catalyst supports (3M Co.) enabled this advance which should significantly ease the stringent CO control requirements that must be imposed on fuel processors.

PE Membranes: There is ample experimental evidence that Nafion-type PE membranes have the fundamental performance and endurance required for use in automotive and other PEM fuel cells, but the prices charged by the few companies that currently supply membranes are in the range of \$600-800 per m^2. While these prices are acceptable for PE membrane applications in chlor-alkali and similar industrial electrochemical cells (currently the main market for the membranes), they are 10-20 times above the low level needed for automotive applications.

The Panel heard two rather different views regarding the future cost of Nafion-type membranes and, consequently, different technical strategies of stack developers and membrane suppliers. In one view — held by the majority of developers and cautiously encouraged but until recently not quantitatively supported by membrane suppliers — large-scale production will reduce the cost and price of Nafion-type PE membranes to acceptable levels, for example, \$50/m^2 or less. At this cost, the membrane would contribute about \$7-10/kW to the cost of a high performance cell stack.

In early 1998, DuPont gave strong support to this view by announcing that its Nafion membrane prices would drop to less than \$50/m^2 for supply of membranes to an annual market of about 150,000 automotive PEM stacks. Such a market would require about 1 million m^2 of membrane per year, or 10 times the current world market. The main reason for projecting this large reduction in membrane costs appears to be that mass production will reduce both, resin and membrane manufacturing costs substantially. Arguments given to the Panel for the possibility of even greater cost and price reductions are that the fluoropolymer (ionomer) resin rather than the membrane might eventually be used to manufacture MEAs, and that membranes might be recovered and reused, with a corresponding economic credit for valuable recycled materials.

The other view — held by a several organizations developing PEM stacks and/or alternate PE membranes — is that Nafion-type PE membranes will always be relatively expensive because of the inherently high cost of fully fluorinated materials. Several of these organizations have developed either partially fluorinated membranes (Ballard), or hydrocarbon-based PEMs (Hoechst). These alternatives have shown competitive performance and sufficient endurance (e.g., ≥5000 hours of operation) to suggest that they may be able to meet automotive application requirements while offering the advantage of substantially lower costs.

The membrane developers/suppliers on both side of the issue are highly credible leaders in their fields, and all of them appear to be committed to develop PE membrane products that will help realize mass markets for fuel cells. Several have, or will shortly have, membrane production capacities sufficient to serve emerging markets for PEM fuel cells. The prospective manufacturers of automotive PEM fuel cell stacks and systems will be the beneficiaries of the emerging competition between membrane alternatives and their manufacturers, and the prospects for commercial availability of PE membranes meeting the performance, endurance and cost goals for automotive applications can be considered very promising.

Membrane-Electrode Assemblies: MEA performance has been advanced to the point where a number of the stack and MEA developers visited by the Panel are reporting current densities in the range of 600-1400 mA/cm^2 at practically usable cell voltages (e.g. 0.6-0.7 V), corresponding to cell-level power densities of around 0.5-0.75 W/cm^2. This level of MEA performance should give a fully developed and properly engineered automotive PEM cell stack of 50-75 kW a specific performance of around 1 kW/liter, the goal for the PNGV and other programs. Through careful optimization of cell design, even higher MEA power densities — for example, 1 W/cm^2 — should be achievable without additional breakthroughs.

MEA costs aggregate from the costs of catalysts and catalyst supports, wetproofing agents, current collectors (e.g. carbon paper), membranes, and MEA manufacturing. The application of large-scale film manufacturing methods by highly experienced companies such as Gore and 3M, now active in MEA development, is likely to reduce MEA manufacturing costs to around $1/kW or below. Thus, the costs of mass-produced MEAs will be determined largely by the highest-cost ingredients: PE membranes and catalysts. With the cost projections the Panel heard (membrane @ $20-50/m^2, corresponding to $2-5/kW for a cell performance of 1 W/cm^2) or was able to infer (catalysts @ $2-3/kW), a cost range of $5-10/kW can be projected for mass-manufactured MEAs. Eventually, this cost might be reduced further by leasing of catalysts and obtaining credit for recycled membranes since both of these high-value materials are likely to be recovered at the end of stack service life. Integration of ionomer resin or resin solutions — rather than finished membranes — into the MEA production process was mentioned to the Panel as yet another promising avenue for MEA cost reduction.

It is significant that MEAs are being developed not only by all major stack developers but also by organizations engaged in membrane and catalyst development. As a result, improvements or perhaps entirely new concepts — for example, a more integrated fabrication of MEAs from its main constituents — can be expected. Even now, high performance MEAs are available in pilot quantities from several suppliers, and the emerging competition should advance the technology and ultimately reduce prices to the levels mentioned above.

Separator (“Bipolar”) Plates: Separator plates are a functionally and economically critical part of fuel cell stacks. Solid, gastight graphite plates with machined gas flow fields have been most widely used as separators for several types of fuel cells. Such plates cost as much as $200/kW — far more than the separator cost acceptable for automotive fuel cells.

Every PEM stack developer is, therefore, engaged in developing low-cost separator plates. The Panel heard about a variety of technical approaches, including use of graphite plates with machined flow fields (almost certainly too expensive); machined, graphite-containing composites; impregnated, molded porous carbon; and plates made from various metals by different techniques and protected by anti-corrosion coatings.

No stack developer appears to have made a final choice, but several approaches look promising, including embossing of impregnated porous carbon, molding of commercially available carbon composites (Energy Partners), embossing of coated metal plates (Allied Signal; Siemens); and perhaps bonding of appropriately shaped metal sheets (H-Power). At present, confident estimates of separator plate costs are still lacking. However, the approaches under development were all selected for their potential to permit low-cost mass manufacturing of plates from inexpensive materials, lending credibility to the $5/kW cost projected by a leading developer.

PEM Cells and Stacks: The remarkable advances in MEA performance discussed earlier (see, for example, Figure III-4) are creating the basis for high performance PEM cells. Equally important for high stack performance, developers have successfully applied thinner separators (including metallic structures) with improved flow fields for reactant gases, developed methods for efficiently removing product water and heat, and introduced better ways of humidifying PE membranes during operation. As a result, the power density of stacks has increased remarkably (see for example Figure III-2), and a further increase to almost 1.5 kW/liter is planned for Ballard's "production" stack. At this level, the volume of a 75 kW stack is reduced to 50 liters — less than 2 cu.ft.

One key finding of the Panel is that PEM stacks are being fabricated by a substantial number of both smaller and large organizations in North America, Europe and Japan, as shown in Table III-1. Most of these still are short, developmental stacks to test the characteristics of key components, verify stack design features, and evaluate approaches to scale-up. A few developers have fabricated developmental stacks in sizes (e.g., 30-50 kW) approaching the requirements for FCEV propulsion, and a number of other organizations — including several funded under DOE's current PRDA (see Appendix E) — are expected to take this important step in the near future.

Ballard, the leading developer, has been fabricating and delivering developmental and preprototype stacks of up to 50 kW in limited quantities for several years. Under the Daimler Benz-Ford-Ballard collaboration, a concerted effort is now underway to establish the basis for low-cost mass manufacturing of the Ballard PEM fuel cell stack technology through development of manufacturing processes for every stack component and for their assembly into complete stacks. These components and techniques will come together in a 75 kW stack intended for production; the design of that stack is to be finalized still in 1998. Pending the decision to proceed with full-scale commercialization of fuel cell electric vehicles, stack pilot manufacturing will begin in 2000. Full-scale production is scheduled to reach about 40,000 stacks per year in 2004 and 100,000 units/year in 2006. Stack costs are likely to drop to $35/kw at the 40,000 units/year level and ultimately to $20/kW.

B. FUEL PROCESSOR TECHNOLOGY

Background

Efforts to convert carbon-containing fuels into hydrogen-rich gas streams for use in fuel cells date back to the gas and electric utility fuel cell programs of the 1960s and 1970s. The primary goals of these programs were to develop phosphoric acid fuel cells into multi-kilowatt to megawatt-level power generators capable of using natural gas and petroleum-derived liquid fuels with high efficiency while producing very low emissions. A number of processing reactions and schemes were explored, with emphasis on the development of sulfur-tolerant catalysts and processes such as high-temperature steam reforming, partial oxidation, and autothermal reforming. Utilizing steam reforming as the primary conversion process, these efforts resulted in development of smaller-capacity fuel processors that were much more compact and capable of operating efficiently over a wider range of hydrogen outputs than industrial steam reformers.

Fuel processors of this type are now part of phosphoric acid-based fuel cell power plants offered commercially, for example by IFC. These fuel processor technologies are optimized for high efficiency under the duty cycles experienced in stationary power generation — typically, infrequent start-ups and constant or slowly varying outputs. They were not developed to meet the stringent power density and start-up time goals for automobile applications as, for example, established by PNGV (see Table II-4).

The feasibility of combining a methanol fuel processor with a phosphoric acid fuel cell stack into a multi-kW automotive power source was first explored at the Los Alamos National Laboratory in the early 1980s. These efforts took advantage of earlier DoD supported R&D on stationary methanol steam reforming which had resulted in development of the copper-zinc catalysts that became the new standard for methanol reforming. The LANL work also established the need for new reformer reactor designs with more rapid response, and it resulted in a design that became the basis of GM’s current methanol fuel processor.

Despite this technical progress, a compact and efficient fuel processor technology suitable for conversion of methanol and/or gasoline on board of automobiles did not exist less than 10 years ago. Since then, a number of fuel processor development efforts have been initiated by three different types of organizations: R&D groups funded under industry-government initiatives to advance PEM fuel cell subsystem and system technologies, automotive manufacturers committed to fuel cell engine development, and more specialized industrial companies with technical competencies and business interests in reformer technology. These organizations, the fuels and processing approaches chosen by them, and their development status are summarized in Table III-8.

The development progress achieved and the outlook for automotive fuel processor technology are discussed in the following sections.

Table III-8. Commercial Organizations Developing Fuel Processor Technology

	Fuel Type Focus		Primary Fuel Processor		CO Conversion Processes		Vehicle Sy Subsyste	
Corporation	Methanol	Gasoline	Steam Reforming	Partial Oxidation	Water Gas Shift	Preferential Oxidation	Primary	Shift
A. D. Little	Second	First[a]		✓[b]	✓	✓	✓	✓
Daimler Benz	First	Second[c]	✓			✓	✓	
GM	First	Second[c]	✓		✓	✓	✓	✓
Honda	Sole		✓			✓	✓	
Hydrogen Burner Tech		Sole[a]		✓	✓			
IFC	First	Second	✓	✓	✓	✓	✓	✓
Johnson Matthey	First	Second	✓	✓[d]	✓		✓	✓
Mitsubishi	Sole		✓		✓	✓		✓
Nissan	Sole		✓		✓	✓		
Toyota	Sole		✓		✓	✓	✓ (?)	✓ (?)
Wellman CJB	Second	First		✓	✓	✓	✓	✓

[a] Diesel fuel has also been reformed successfully

[b] Steam is added downstream of the partial oxidation reaction but prior to the catalyst bed

[c] Gasoline processor likely to differ from methanol processor

[d] Partial oxidation is combined with steam reforming in a process similar to autothermal reforming

[e] Designed for bus applications

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Technology Status: Government-Industry Programs

1. Arthur D. Little

Under DOE contract, ADL has completed a series of phased efforts beginning more than 5 years ago with conceptual and design studies of various approaches to the processing of ethanol, methanol and gasoline. Several stages of hardware fabrication and improvement over the past 3 years resulted in a 50 kWe[1] fuel processor consisting of the functional process units shown in Section II (see Figure II-4).

The performance and operating characteristics of ADL's fuel processor are summarized in Table III-9.

Table III-9. Characteristics of the ADL Flexi-fuel Reformer[a]

Maximum Unit Size:	50 kWe
Power Density:	0.7 kWe/liter
Specific Power:	0.5 kWe/kg
Energy Efficiency (LHV):	78% (50 kWe), 73% (32 kWe)-Gasoline 84% (50 kWe), 82.5% (40 kWe) - Ethanol
Start-up to Full Power:	2 min.
Turndown Ratio:	5:1 to 7:1
Transient Response:	3-5 sec. (10% - 90% of load)
Projected Cost:	\$16 - 25/kW

[a] Does not include PROX unit

The primary processing method chosen by ADL is a combination of thermal partial oxidation and catalytic steam reforming. Air and fuel are added at the reactor inlet which does not contain a catalyst; carbon formation is suppressed by preheating the air and adding steam. The reaction product contains hydrogen, carbon dioxide, carbon monoxide and methane. As these gases pass through the steam reformer catalyst bed, most of the methane reacts with steam to form more hydrogen, carbon dioxide and carbon monoxide. Further downstream, undesirable CO is converted to hydrogen and carbon dioxide by the water gas shift reaction.

Finally, in a separate catalytic "preferential oxidation" (PROX) unit the concentration of CO is reduced to about 10 ppm by adding air to oxidize CO to CO_2 selectively, that is, in preference to the valuable hydrogen content of the gas stream. The hydrogen concentration in

[1] kWe is the hydrogen production rate or capacity (expressed in electric power units) that is needed to meet the hydrogen demand of a fuel cell stack operating at the numerically same kW power output.

the fuel processor output approaches 40% for gasoline, about 45% for ethanol. The remainder of the gas consists of CO_2 and nitrogen (approximately 30%) which are inert in the fuel cell stack.

To achieve the reported 78% thermal efficiency for processing of gasoline into hydrogen, close thermal integration of the exothermic process steps (partial oxidation and water gas shift) with the various endothermic steps (fuel vaporization, steam generation, air preheating, and steam reforming) is essential. This requirement complicates design and construction of the fuel processor considerably.

In a recent proof-of-concept demonstration funded by DOE, an ADL reactor (without a PROX selective oxidation unit) was coupled to a two-stage PROX device provided by LANL. The resulting experimental fuel cell processor had overall thermal efficiencies of 73% and 82.5% when operating on gasoline and ethanol, respectively. (As noted in Section II.3.A, processor efficiency is defined as the ratio of hydrogen output and fuel input heating values.) The hydrogen output of this processor was used to operate a small PEM fuel cell stack supplied by Plug Power.

Further development of ADL's fuel processor will focus on changing catalyst configurations from pelleted to monolithic supports, integrating a PROX unit, and reducing PROX platinum catalyst loadings. Automated control will be expanded to include the PROX unit. ADL expects to supply 50 kWe fuel processors to several of the current DOE funded fuel cell system integration efforts discussed further below and summarized in Appendix E.

These activities should result in a better understanding and eventual optimization of fuel processor systems operation, in particular reduction of the very high CO levels observed during load transients. Other goals are to provide low-cost solutions to thermal and water management and to the control of the complete fuel processor. Representative fuel processor emissions data apparently are not yet available but ADL is projecting that emissions will meet the most stringent future standards.

ADL's analysis suggests that fuel processor cost would drop from about \$130/kWe for a production volume of 100 units/year to \$16-25/kWe for 10,000 units/year which probably would be acceptable for automotive fuel cell applications (see also Section III.1.E, below). A major automobile manufacturer has reviewed ADL's estimates and considers them realistic. Recently, ADL formed the Epyx Corporation to commercialize fuel processor technology, initially for hydrogen production and stationary fuel cell power generation. The technology advancement, manufacturing development and production cost learning expected under this initiative should benefit automotive applications as well.

2. Mitsubishi

Under the aegis of the MITI/NEDO PEM fuel cell program, Mitsubishi Electric is developing a methanol reformer for a 10 kW fuel cell stack intended for portable power and hybrid vehicle propulsion applications. Mitsubishi has adopted a novel reactor design in which corrugated aluminum plates are stacked and the voids between plates are filled with small catalyst pellets.

Because of the very good heat transfer permitted by this design, reformer startup can be rapid and temperature is very uniform, both important features for automotive applications which call for high reformer power density. Two other functional components of the reformer system — the methanol-water evaporator and the perforated-plate catalytic combustor for the anode exhaust gas — also are arranged in plate form and physically as well as thermally integrated with the reformer stack.

A 1 kWe laboratory reformer has been constructed by Mitsubishi and is now being tested for functionality and endurance when operated at atmospheric pressure, and a 2-stage CO selective oxidation reactor is under development. On the basis of the current design, a 50 kWe methanol reformer would occupy a volume of approximately 125 liters (0.4 kW/liter). Mitsubishi's goal is to reduce this volume to about 27 liters by reducing the thickness of the reformer plates. If successful, this would yield the attractive specific power of 1.85 kW/liter for the reformer excluding the PROX (preferential oxidation) unit.

At this stage, there appear to be no plans for upscaling beyond the NEDO 10 kWe target. Engineering design and manufacturing development of a scaled-up Mitsubishi methanol fuel processor for automotive applications if undertaken would become part of the corporation's in house activities. In that case, Mitsubishi would provide all engineering design and manufacturing of their advanced reformer, and cost reduction would be a major objective inasmuch as projections based on the current concept indicate that manufactured cost would still be too high. Finally, Mitsubishi's view appears to be that automotive fuel cell engines would be part of a fuel cell-battery hybrid power plant, with somewhat less severe design constraints for the fuel processor.

3. Wellman CJB

Over the past 15 years, this UK firm has supported UK and other European government-funded PEM fuel cell R&D by providing fuel processing expertise and technology for programs such as JOULE II and FEVER. Wellman's fuel processing activities have been funded also by DOE and the European Space Agency, and the company has been or is working with DeNora, Ballard and other organizations engaged in fuel cell technology and system development.

Wellman's technology focus is steam reforming and partial oxidation of methanol, gasoline and diesel fuel. They have special expertise in hydrogen purification by means of diffusion through palladium alloy thin film separators but also work on CO preferential oxidation. Wellman has developed novel reforming catalyst structures by coating alumina foam or aluminum plates with copper/zinc catalyst. This approach permits rapid transfer of heat to the endothermic steam reforming reaction directly through the catalyst. Wellman has built bench-scale plate and tubular reforming reactors to demonstrate their approach and has designed compact reactors that take advantage of its special features.

Technology Status: Fuel Cell System Developers

1. Daimler-Benz

DB has been developing methanol reformer/fuel processor concepts and technology for automotive applications since the beginning of its collaboration with Ballard in 1993. These efforts resulted in the development of a 50 kWe fuel processor comprising a steam reformer and a CO selective oxidizer. This fuel processor is used in the methanol fuel cell "breadboard" system that powers the NeCar 3 experimental vehicle which was demonstrated in September 1997 as the world's first fuel cell electric automobile.

While this processor is not yet a prototype, it is a fully functional assembly of the process units required for on-board conversion of methanol into a low-CO, hydrogen-rich fuel stream compatible with the Ballard 50 kW fuel cell stack of the NeCar 3 vehicle. The performance and operating characteristics of this methanol processor are as follows:

Table III-10. Characteristics of the Daimler-Benz Methanol Processor

Maximum Unit Size:	50 kWe
Power Density:	1.1 kWe/liter (reformer=20 l, combustor=5 l, CO selective oxidizer=20 l)
Specific Power:	0.44 kWe/kg (reformer=34 kg, combustor=20 kg, CO selective oxidizer=40 kg)
Energy Efficiency (LHV):	Not determined
Methanol Conversion Efficiency:	98 - 100%
Start-up to Full Power:	Not applicable — recirculated oil is thermal medium
Turndown Ratio:	Vehicular operation (20/1)
Transient Response:	<2 sec
Projected Cost:	Not applicable to this unit

Recently, the Daimler Benz team obtained the first data on pollutant emissions from the NeCar 3 fuel processor while the vehicle was operated on a dynamometer programmed for a representative urban/suburban driving cycle (FTP75) but excluding cold start. The measurements indicate that processor (= vehicle) emissions were either zero (for both NO_x and CO) or extremely low (total hydrocarbons ≤0.005 g/mile). Daimler-Benz considers these results preliminary since the data have not yet been replicated to establish a statistically significant base and do not include the effect of cold start. Nevertheless, they suggest that fuel cell electric engine and vehicle emissions will indeed be zero or near-zero, as has been generally assumed.

The operating experience with the DB experimental methanol processor is being used in the ongoing development of next-generation processor component technologies and their integration into processors of low thermal inertia. Heat exchangers, catalyst beds, and the selective oxidizer units are being developed into configurations meeting the goals of rapid start and response, compactness, reliability, and manufacturability at low cost in mass production. Engineering design for manufacturability and the beginning of manufacturing development already are integral aspects of DB's methanol fuel processor development program. Although the current focus is on processing of methanol, DB also has a low level effort investigating gasoline processing. Fuel processor complexity is thought to be greater and efficiency less than the methanol processor planned for the immediate future, but DB appears prepared to develop a gasoline fuel processor should methanol availability be too limited in the foreseeable future.

2. General Motors

Over the past several years, GM has been working on a methanol fuel processor for an automotive PEM fuel cell, consistent with the broad agreement between the major U.S. automobile manufacturers that GM focus particularly on methanol, Chrysler on gasoline and Ford on hydrogen as fuels for automotive PEM fuel cells.

The basic design of GM's steam reforming-based fuel processor originated in the DOE-funded program at Los Alamos National Laboratory but was developed further at GM, with the objective to integrate and test the processor with a 30 kW PEM stack as a system; its main features are as follows:

Table III-11. Characteristics of the GM Methanol Fuel Processor

Maximum Capacity:	30 kWe
Power Density:	0.5 kWe/liter
Specific Power:	0.4 kWe/kg
Energy Efficiency (LHV):	82 - 85%
Methanol Conversion Efficiency:	>99%
Start-up on Automatic Control	
Turndown Ratio:	Not determined
Transient Response:	Not determined
Projected Cost:	Not applicable to this unit

Like Daimler Benz' NeCar 3 methanol processor, the GM unit is not yet a packaged prototype and does not meet the requirements of rapid start-up and transient response. Rather, it is a functional assembly of the main fuel processing units (including a PROX reactor), to evaluate component and fuel processor performance, and to permit study and resolution of integration issues. A 30 kW fuel processor-PEM fuel cell laboratory system has now been assembled by GM for these purposes.

GM identified several areas where substantial improvements of fuel processor technology are required, including catalyst configurations with potential for long life, better heat utilization for improved efficiency, and more rapid start-up and transient response through reduction of thermal inertia and better heat transfer. While some of the functional components — for example, controls — used by GM already reflect automotive industry practice, design and engineering of fuel processor components and systems for compact packaging and low cost mass manufacturing still are largely ahead.

In a parallel effort, a GM business unit is supplying Chrysler with an integrated fuel processor-PEM stack fuel cell system under the joint government-industry initiative of DOE's transportation fuel cell plan.

3. Honda

Honda is working in-house on a methanol fuel processor that uses autothermal reforming of methanol. In addition, Honda's fuel processor will have a water gas shift reactor as well as a selective oxidizer for control of CO concentrations in the processed fuel stream entering the fuel cell stack. Testing of subsystems is ongoing but a fully integrated processor has not yet been operated. Thus, no performance and efficiency data are available at present.

Honda has set goals for fuel processor weight, volume and cost (not disclosed to the Panel) but is still considering several processor system design alternatives. The final decision will be closely linked to the selection of the FCEV drive system configuration. Honda's goal for emissions from the fuel processor and vehicle is less than 10% of ULEV standards, but no data on actual emissions are available at this early stage of processor development.

4. International Fuel Cells

IFC has been developing fuel processing technology for 25 years, with emphasis on natural gas and light distillate processors for stationary phosphoric acid fuel cell systems. Steam reforming continues as the technology of choice for this application, chiefly because of its high efficiency which arises from the ability to utilize waste heat from the stack (for raising process steam and/or heating water), and from burning of unconverted fuel to drive the endothermal steam reforming reaction. In IFC's PC25, for example, the thermal efficiency of the natural gas steam reformer is about 86%.

Since 1995 IFC has been engaged in adapting its fuel processor and phosphoric acid fuel cell technologies to the propulsion of buses, as part of a DOE/DOT-sponsored program at Georgetown University. Reformer volume has been reduced from about 250 ft^3 for the PC 25 (about 0.03 kWe/liter) to 45 ft^3 for a 100 kWe reformer (about 0.08 kWe/liter) used in IFC's bus fuel cell power plant, with further improvements projected. Nevertheless, these reformer power densities are far below 0.5 kWe/liter, the target for automobile applications (see Table II-4). Another issue with steam reforming is the rather long time (in the case of the PC 25 reformer, hours) required to bring the system to operating temperature since heat must be provided from outside the reformer, in contrast to partial oxidation-based processors which can utilize the heat of reaction generated within the processor.

One important result of IFC's engagement in bus fuel cell power plant development is the measurement of pollutant emissions. These emissions arise from the combustion of natural gas in the reformer heater which must take place above the temperature of the steam reformer (about 980°C for methane) but were found to be extremely low: about 0.5 ppm NO_x, 2 ppm CO, 4 ppm total carbonaceous gases, and no smoke (particulates). Since gasoline reforming takes place at similar temperatures, emissions from a gasoline reformer heater should be similarly low. Even lower emissions (especially of NO_x) can be expected for methanol fuel processors because the much lower reformer temperature required for methanol allows the catalytic combustor to be operated at correspondingly low temperatures.

Recently, IFC has announced a corporate commitment of resources to the development of automotive PEM fuel cell technology based on IFC's PEM stack and fuel processor technologies. Details of the technical approach to be pursued have not yet been provided. It seems clear, however, that the automotive processor technology will have to be substantially different from IFC's natural gas steam reformers to meet the goals of high specific performance, rapid start-up and low cost.

5. Toyota

In the early phase of their fuel cell program, Toyota concentrated on hydrogen as fuel and the development of a compact, metal hydride-based system for on-board storage of hydrogen. Recognizing the opportunities for development of PEM automotive fuel cells without (or ahead of) establishment of a hydrogen fuel infrastructure, Toyota initiated an in-house effort to develop a fuel processor for methanol.

Toyota's technical approach to methanol processing is based on steam reforming; no separate shift reactor is used downstream from the steam reforming process unit. Use of a ruthenium catalyst in the PROX unit helps reduce CO concentration by methanation. Toyota presently is addressing several of the most important but difficult challenges that must be met by automotive fuel processors: Reliable and rapid start-up; control of CO to the low levels required by the PEM fuel cell; and compact design. With the exception of the reformer and selective oxidizer catalysts which are purchased, Toyota's fuel processor components and system are being developed in house with corporate funding.

For a fully developed and packaged methanol reformer of 25 kWe capacity, Toyota projects a tubular volume of 0.3 m diameter and 0.6 m length, corresponding to a power density of about 0.6 kWe/liter. However, it was not made clear to the Panel to whether Toyota already has a design basis for packaging its methanol reformer/fuel processor into this volume, or how far component design for manufacturability and manufacturing development have proceeded.

<u>Technology Status: Other Industrial Developers of Fuel Processing Technology</u>

1. Hydrogen Burner Technology (HBT)

Over the past 5 years, this small Californian company has developed a partial oxidation process to generate hydrogen from various petroleum-based fuels, including Diesel fuel and JP-8.

In the HBT process, partial oxidation of the fuel is carried out with preheated air at pressures up to 10 atmospheres and followed by a high temperature water gas shift reaction to reduce the CO concentration. Pressure-swing absorption (PSA) is then used to purify hydrogen to 99.99%, and the low-heating value gas rejected from the separation unit is used to preheat air and fuel.

HBT's fuel processor (without the PSA purification unit) originally was intended for application in fuel cell power plants. However, HBT now is targeting its processor for production of high purity industrial hydrogen. To serve this market, HBT currently is producing small numbers of fuel processors in capacities of 7 and 42 kWe. Such units also could supply hydrogen on site for hydrogen-air fuel cell fleet vehicles such as buses if and when a market develops.

2. Johnson Matthey (JM)

Motivated by a strong interest in fuel cells as a potentially important business area, Johnson Matthey (JM) has been supporting a corporate R&D effort on fuel processing for fuel cell applications for the past 10 years. This effort has resulted in the development of the HotSpot® methanol fuel processor. HotSpot consists a number of tubular autothermal (partial oxidation plus steam reforming) reactor modules feeding into a single selective oxidation (PROX) module. Rapid heating is accomplished with the heat released by the partial oxidation of methanol in the individual reactor tubes. Catalytic combustion of residual hydrogen in the anode exhaust, supplemented by burning of some methanol, provides the heat required to evaporate the methanol-water processor input.

JM has assembled an 8-module HotSpot fuel processor with the characteristics shown here:

Table III-12. Characteristics of Johnson Matthey HotSpot® Fuel Processor[a]

Maximum Capacity:	6 kWe System (8-0.75 kWe reformer modules)
Power Density:	0.5 kWe/liter
Specific Power:	0.5 kWe/kg
Energy Efficiency (LHV):	89% (95.4% reformer-93.5% CO clean-up)
Conversion Efficiency:	>99%
Start-up:	20 sec to 75% rated output 50 - 60 sec to maximum rated output
Turndown Ratio:	Not available
Transient Response:	Not tested
Projected Cost:	Plan to meet PNGV goal

[a] Complete reformer, CO clean-up, catalytic burner system

The small size and thermal mass of the individual processor tubes, and the possibility to temporarily increase the extent of exothermic partial oxidation by adding more oxygen to the input fuel, help achieve start-up times much shorter than those reported by other developers. Power density also is promising (see Table III-12). No emissions data are available as yet but use of a catalytic combustor should result in extremely low emissions of NO_x and carbonaceous gases.

JM is still improving the technology, with emphasis on higher power density, reduced pressure drop, improved heat balance, higher efficiency, and development of appropriate controls. According to JM, the next-generation HotSpot processor will require only half the volume for the same processing capacity. A 6 kWe methanol processor assembled from 8 of the improved modules is projected to have the excellent power density of nearly 1.2 kWe/liter and a specific power of about 0.8 kWe/kg. Adding one of JM's improved CO selective oxidizers to the 8-module processor is expected to result in a complete methanol processor with the attractive power density of approximately 1kWe/liter. JM is now investigating the design modifications needed to give its technology the capability to also process gasoline.

In parallel, JM is collaborating with Volkswagen to define the design and operating characteristics of a HotSpot multi-module processor integrated with a PEM fuel cell stack into a breadboard fuel cell power plant. This project is part of the CAPRI initiative of the European Commission under which a VW Golf vehicle will be fitted with a 24-module, 20 kWe HotSpot fuel processor linked to a PEM fuel cell stack.

No plans for manufacturing development and manufacturing of the HotSpot fuel processor technology were mentioned by JM staff, and no cost projections were available. However, the modularity of the technology should provide the economies of mass production at substantially smaller annual rates of fuel processor capacity production than other, non-modular technologies.

Summary and Outlook, Fuel Processor Technology

Technology for processing of natural gas and light petroleum distillates has been developed successfully for the phosphoric acid fuel cell power plants now being commercialized for electric power generation. That processor technology, however, cannot meet the stringent performance and cost criteria imposed by automotive applications. Because the fuel processor is an essential part of PEM automotive fuel cell engines that must operate on methanol, gasoline or other liquid carbonaceous fuels, a number of organizations have become engaged in automotive fuel processor development during the past 5-10 years. Most of these efforts (especially those in Europe and Japan) focus on processing of methanol but gasoline and multi-fuel processors are receiving increasing attention, especially in the U.S.

While the basic chemical reactions and commercial industrial processes for conversion of hydrocarbons into hydrogen-rich fuel gases are well established, automotive fuel processors must meet unprecedented requirements for high power density (compactness), rapid start-up and dynamic response, high efficiency, near-zero emissions and very low cost. A number of developers are addressing this challenge with significantly different and often novel designs but methanol and gasoline fuel processors have not yet reached the level of development attained by fuel cell stack technology. Nevertheless, important advances have been made. Those considered particularly significant on the basis of the Panel's discussions with developers of fuel processing technology are summarized in the following.

Methanol Fuel Processing Technology. Most of the current fuel processor development efforts focus on methanol. Steam reforming or autothermal reforming are the two primary conversion processes being employed by developers. Water gas shift reactors are used in a secondary step to reduce the CO content of reformer output. In a final processing step, CO content is reduced to the levels tolerated by the stack (about 10 ppm, up to perhaps 100 ppm for some PEM MEA/cell technologies) by selectively oxidizing CO in preference to hydrogen. These steps have been demonstrated individually on the laboratory process unit level by at least five different organizations (see Table III-8).

Platinum catalysts appear to be required for the selective oxidation reactor; the other process steps use copper/zinc and nickel catalysts. Although quantitative information on the amount of catalysts used in the various process units is generally lacking, there seems to be a general consensus that fuel cell processor catalysts (including the platinum catalyst used in PROX units) will not be a cost issue once these catalysts are used efficiently in the proper support-catalyst configurations. In Toyota's approach, ruthenium is added to the selective oxidation (PROX) catalyst to also promote the methanation of CO. This approach helps to reduce the CO concentration entering the stack over a range of temperatures and flow rates.

The need for at least two and typically 3 (or even 4) coupled process units complicates the design, construction and control of methanol fuel processors considerably. Nevertheless, about half a dozen developers have assembled the functional units into "breadboard" processors. Several of these are now being operated to develop data on integration issues, start-up and dynamic characteristics, power density, emissions and efficiency. The integration of fuel cell processors with stacks and auxiliary equipment into complete fuel cell systems is discussed in the Section III.1.D below.

In no case do the current methanol processors represent prototypical technology. Available data (see e.g., Tables III-9 through 12) are, therefore, not necessarily indicative of ultimately achievable performance. From this perspective, the power densities already achieved (typically around 0.5 kW/liter) are quite encouraging, as are the high fuel conversion rates and good thermal efficiencies. On the other hand, start-up times typically are many minutes since thermal management of the process units and integration of the experimental processors are not yet fully developed. The rapid start-up capability of the Johnson Matthey methanol processor, a notable exception, points to the advantages of modular construction although it remains to be established that thermal integration and control of multi-module processors are technically and economically feasible.

At this stage, little information is available on fuel processor cost[2]. With the exception of the PROX reactor platinum catalyst (which most likely will be used in small amounts only) the materials used in the various fuel processor units are inexpensive. Fuel processor cost will, therefore, be determined largely by the cost of manufacturing the process units and integrating them thermally and physically into an efficient and compact system. As a consequence, confident cost estimates will be possible only after designs of fuel processor units and systems engineered for low-cost mass manufacturing are developed — probably over the coming 2 years for the leading programs. In the meantime, preliminary cost estimates such as ADL's (see below) suggest that fuel processors will be able to meet the stringent automotive cost targets but only in mass production.

<u>Gasoline Fuel Processing Technology</u>. Development of gasoline processors suitable for automotive applications began relatively recently. With funding from DOE and PNGV, Arthur D. Little adapted ethanol processor technology (developed previously with DOE support) to gasoline processing. In principle, ADL's technical approach (thermal partial oxidation followed by steam reforming, water gas shift and PROX units) permits rapid start-up and processing of a wide variety of carbonaceous fuels. The trade-off to these desirable characteristics is a somewhat lower thermal efficiency. The levels of complexity (and, thus, cost) of ADL's 3-unit fuel processor should be comparable to the methanol processors discussed above. Its estimated cost of $16-25/kW appears compatible with the cost constraints for a fuel cell automobile engine (see also Figure III-5, below) but the basis for this estimate implies considerable uncertainty of costs. Other significant uncertainties that remain to be resolved include efficiency and emissions over representative duty/driving cycles, tolerance for impurities in methanol and/or gasoline, and the chemical and mechanical stability of processor catalysts under representative fuel and driving conditions.

[2] The costs of the natural gas fuel processors for phosphoric acid fuel cell systems being commercialized in small numbers for electric power generation are very high but not indicative of the prospective costs of mass manufactured automotive fuel processor technology.

At this time, ADL appears to be the only organization that has reached the breadboard stage but other U.S. efforts (Delphi/Chrysler; IFC) are now underway with the goal of developing gasoline processors for PEM automotive fuel cell engines. The next several years of development, integration, testing and manufacturing development can be expected to yield much of the information required to assess the technical and cost prospects of gasoline fuel processors. Emergence of fully competitive gasoline processors would significantly enhance the prospects of fuel cell electric vehicles and of gasoline to become the fuel of choice.

C. BALANCE OF PLANT

Air Management

Most developers of PEM fuel cell power plants for automotive applications are concentrating their development efforts on systems operating at 2-3 atmospheres because pressurization can result in more compact and potentially lower-cost fuel cell engines. However, and as discussed in Section II.2.C low-cost turbomachinery to efficiently pressurize fuel cell systems in the small capacities required for automotive applications is not commercially available, and inefficient turbomachinery can reduce system efficiency by 30% and more.

Although this issue should be of significant concern, automobile manufacturers engaged in PEM fuel cell system development as yet do not seem to have identified appropriate compressors and expanders for their systems. Even some major fuel cell power plant developers appear to underestimate the difficulty to obtain suitable equipment. Suitable in this context means turbomachinery that meets highly restrictive requirements with respect to size, weight, efficiency over a wide operating range (large turndown ratio), noise and cost.[3] Another important need is turbomachinery that can function without contaminating the process air for the stack with lubricating oil.

Given this situation, it is perhaps not surprising that IFC, the developer with the most experience with pressurized fuel cell systems, has opted for atmospheric pressure operation which requires only a blower for moving air through the system. In support of that decision, IFC claims to have advanced-technology PEM stacks that have sufficient performance at ambient pressure. Also, some European developers seem to be moving toward lower levels of pressurization: DeNora noted the preference of one European automobile manufacturer for stack operation at ≤1.5 atmospheres, and Siemens mentioned a similar goal for its PEM fuel cell technology.

[3] Cost criteria and goals apparently have not yet been defined for fuel cell turbomachinery.

Daimler-Benz is working with the 3 atm Ballard stack technology although lower pressure levels apparently are under consideration as well. Characteristic for its comprehensive approach to fuel cell engine development, DB has been developing a compressor-expander unit in house but efficiency apparently is not yet satisfactory over the large turndown ratio required. None of the Japanese automobile manufacturers mentioned substantial turbomachinery development efforts.

Toyota's stacks are operated at about 0.5 atm which, according to Toyota technical managers, requires only a compressor but no expander for acceptable system efficiency. Nissan appears to aim for ≥2 atm operation and is conducting some inhouse work on pressurization. Honda noted a goal of ≤2 atm, but no mention was made of turbomachinery development efforts.

In view of the apparent need for advanced turbomachinery, DOE awarded three development contracts (Allied Signal, ADL, Vairex) in 1996 with the goals summarized here:

Table III-13. DOE Development Goals for Automotive Fuel Cell Turbomachinery

Capacity (air flow rate):	76 g/sec
Input (shaft) Power:	4.3 kW
Weight:	3 kg
Volume:	4 liters
Noise:	≤80 db

To date, no developer has met all goals, and the work was extended into Phase II efforts that focus on extending efficient operation to lower flows (Allied Signal), efficiency improvements (all contractors), and reduced size and weight (ADL). A new contract was awarded to Meruit for two prototype turbocompressors featuring gas bearings for more efficient and contaminant-free operation. One of the Phase II turbocompressors will be mated to a 50kW stack from the programs funded under DOE's current PRDA..

In summary, most automotive fuel cell developers appear to have assumed until recently that timely availability of efficient, compact and potentially low-cost air handling turbomachinery for stack pressurization was not a significant issue. Although simple thermodynamic calculations suggest the feasibility of constructing such equipment, manufacturers of small turbomachinery have known for many years that it is difficult to meet the combined goals of compactness, high efficiency over a large turndown ratio, and low cost. Efforts are now underway to reach these goals— in some cases with unconventional technology — but success has been elusive. Unless significant advances are achieved in the not-too-distant future, unavailability of suitable turbomachinery may force PEM fuel cell engine developers to adopt lower stack pressures and develop ways of compensating for the attendant loss in performance.

Water and Thermal Management

Most organizations engaged in PEM fuel cell power plant/engine development now have at least preliminary system designs that specify water and thermal management approaches and components. However, only Daimler Benz already is in a position to test and evaluate the design and effectiveness of the water management subsystem and its integration with the various parts of the power plant in the rolling test bed of the NeCar 3 methanol fuel cell vehicle. The Panel assumes that Toyota has, or will soon have, a similar capability with its experimental FCEV.

GM has a bench scale test bed which allows water and thermal management to be evaluated under laboratory conditions, and the Chrysler-Delphi team is planning to build a breadboard-level gasoline fuel cell engine that will have a similar capability in the foreseeable future. Although ADL has done a bench test of a fuel processor-fuel cell stack assembly, the mismatch of the subsystem capacities limits the usefulness of any data for the design and performance of future water and thermal management systems. All these efforts still need to establish specifications for materials compatible with water of the prospective purity and temperature levels used in the system.

Heat exchangers, key components of thermal management systems, are commercially available in a very wide choice of materials, design concepts, sizes and specific configurations. However, their applications in the various parts of an automotive fuel cell engine place special requirements for durability, efficiency, compactness and low cost on heat exchangers. As with the water management subsystem, only the organizations mentioned above presently have access to test beds offering representative chemical environments, mass flows and heat transfer requirements for evaluation and optimization of heat exchangers and thermal management. The need for low cost and high performance heat exchangers is now being addressed by some of these organizations with development of novel designs and fabrication of advanced components.

Two important components of the thermal management system — the catalytic combustor/ burners for the anode tail gas and, respectively, for fuel used to heat the vaporizer and the steam reformer — also are presenting development challenges because of the need for clean and complete combustion, durability, and low cost. Daimler Benz/Ballard, GM and ADL have been working on catalytic combustors, but successful operation over the required wide thermal power and dynamic range has not yet been claimed, and decisions for specific equipment have not yet been made.

Whether advanced water and thermal management technologies directly applicable to automotive fuel cell engines exist beyond these investigation is questionable in the Panel's view. Experienced developers of stationary fuel cell power plant technology like IFC, Toshiba and other organizations undoubtedly have the capability to design and implement effective water and thermal management components and subsystems for various fuel cell system types. However, these technologies are designed for significantly larger systems and less severe cost constraints. The need for development of efficient and potentially inexpensive water and thermal management components and subsystems — and the capabilities for manufacturing them — thus become part of the long list of tasks and challenges being faced by the developers and prospective manufacturers of PEM automotive fuel cell engines.

Controls

As noted in Sections II. 2.D and II.2.E, numerous parameters need to be controlled accurately and reliably to assure safe and efficient operation of fuel cell subsystems and power plants over the wide range of conditions and power demands they will encounter in practice. Typically, many different technical solutions to these control requirements are possible. Which control philosophies and components are selected will likely be specific to the various fuel cell subsystem and system designs; the requirements for high reliability and the lowest possible cost will dictate the approaches chosen.

Controls appear to be fairly well developed for fuel cell stacks, but this is not the case for fuel processors, much less for complete, integrated fuel cell power plants. While leading fuel processor developers such as ADL, Daimler-Benz, GM, IFC and Johnson Matthey have had to evolve the necessary controls, as a rule these do not yet meet the criteria for commercial viability. Only a few organizations (Daimler-Benz, GM and probably Toyota) have developed the controls necessary for operation of complete fuel cell systems, but the controls used at this stage are unlikely to meet all reliability and cost goals. Control hardware, software (algorithms) and systems suitable for future fuel cell electric engines thus still need to be developed and engineered for low-cost production.. This development is likely to benefit greatly from the experience of automobile makers with engineering and manufacture of mechanical, electric and electronic control technologies.

D. SYSTEMS INTEGRATION

Proper integration of subsystems is essential for efficient and reliable operation of a fuel cell power plant. As discussed in Sections II-2.E, II-3 and II-4, the requirement for operability on carbonaceous fuels, and the constraints on space and costs imposed by the automobile application, make integration a very difficult challenge.

This challenge is substantially reduced for hydrogen-air fuel cells because no fuel processor is needed. The evolution from the hydrogen-powered NeCar 1 to NeCar 2 vehicles of Daimler Benz and the hydrogen bus of Ballard show impressive progress in PEM fuel cell power plant integration. However, even these power plants are not fully integrated, prototypical engines in that they lack efficient compressors/expanders, provisions for rapid start up in cold weather, and freeze protection for their water supplies. Also, power plant subsystems are not yet matched sufficiently well to give the highest possible efficiencies, especially under off-design and transient conditions.

The Georgetown/DOE/DOT buses represent important advances in the more difficult problem to integrate a steam reforming-based fuel processor with a phosphoric acid fuel cell into a fuel cell engine that can use a liquid carbonaceous fuel. But these fuel cell systems, too, still lack a number of the features required of complete automotive engines. Thus, from the Panel's observations, PEM fuel cell systems integrated on the level required for propulsion of automobiles have not yet been achieved. This objective, recognized as a very difficult challenge by fuel cell system/engine developers, is presently being pursued by a number of competent organizations In the United States, Europe and Japan. The Panel's findings are summarized here.

<u>North America</u>

<u>Allied Signal</u> has two divisions (Aerospace; Automotive) collaborating in PEM fuel cell technology, systems integration and manufacturing development. Focal points of development efforts include a 60 kW stack operating on processed gasoline, an efficient compressor/expander air management system, and systems integration; fuel processor development is subcontracted. Subsystem integration into a complete fuel cell power plant has not yet been attempted, but Allied has the systems experience required for this critical step.

<u>Ballard</u> has extensive experience with integrating its PEM fuel cell stacks into complete power plants/engines for hydrogen-fueled buses and, working with Daimler-Benz, in the NeCar experimental vehicles. DBB Fuel Cell Engines, one of the companies formed as a result of the alliance between Daimler-Benz and Ballard, is developing the next-generation fuel cell engines for buses and automobiles. DBB is responsible for the power plants/engines of the Chicago and

Vancouver buses, and the company is completing the development of a 100 kW methanol-fueled PEM fuel cell system for the 40-foot Georgetown/DOT bus.

Chrysler is working with Delphi on a gasoline-fueled PEM fuel cell system for a fuel cell-battery hybrid power plant to establish proof-of-concept in early 1999. Ballard will supply the PEM stack, Chrysler the controller, battery and motor, and Delphi the balance of the system including the fuel processor. The system will be designed to operate at discrete power levels, and the battery will have sufficient capacity to provide power during fuel cell system warm-up and manage the power transients between state points.

Ford's system efforts include collaboration with IFC (see below) and Daimler-Benz/Ballard. Ford has proposed to DOE a 30-month program to integrate a fuel cell power plant into its P-2000 lightweight vehicle that will serve as a laboratory demonstration vehicle. The Canadian Government already has awarded a contract to Ballard for supply of the hydrogen-air fuel cell engine that is to be used. Ford's participation in the Daimler-Benz/Ballard program should further enhance what already are leading-edge efforts in the integration of hydrogen-air automotive fuel cells.

General Motors brings extensive experience in battery power system integration to fuel cell engine development but recognizes that integrating the primary fuel cell subsystems into power plants is far more difficult. GM's participation (mostly through Delphi; stack from Ballard) in a DOE-sponsored development of a 50 kW methanol fuel cell system provided initial experience with complex issues of systems integration. Much of GM's expanding fuel cell engine and vehicle program will be addressing systems integration approaches and issues.

IFC has extensive fuel cell systems and integration background from its continuing involvement with fuel cell technologies and systems for space power (alkaline stacks) and terrestrial power generation (phosphoric acid stacks). More recently, the Georgetown/DOE/DOT bus project provided IFC with a learning experience in the integration of fuel cell power plants into buses. Also, the development of a 50 kW PEM hydrogen-air fuel cell system jointly with Ford under DOE contract has given IFC experience with system integration issues, power densities and start-up times approaching automotive requirements. The corporation is now focusing efforts on gasoline-fueled processors and PEM stacks for automobile applications with their difficult integration challenges. In pursuing this objective, IFC may be able to achieve a potentially significant advantage if its near-ambient pressure stack technology can be made to operate at the required high power density. This would reduce the complexity and cost of the air management system and the fuel cell system overall (see Section III. C).

Plug Power (see Section II.1.A for corporate and fuel cell background) has strong system capabilities. Teamed with ADL (fuel processing), Texaco (environmental testing) and MarcoTech (automobile component technology), Plug Power under a DOE PRDA will be constructing a 50 kW "fuel-flexible" fuel cell power plant intended to demonstrate stand-alone operation in 2000. Plug Power expects automotive fuel cells to benefit from its technology and systems integration efforts in pursuit of power generation applications.

Europe

Ansaldo Ricerche in Genoa, Italy is part of one of Europe's leading organizations in power plant technology. Ansaldo has been active in development and demonstration of phosphoric acid fuel cells for power generation and has extensive energy and fuel cell systems experience. In the area of hydrogen-air PEM fuel cell technology, Ansaldo has served as system integrator and partner of automobile manufacturers in several European Commission programs. Although Ansaldo has worked on a methanol fuel processor, the company does not appear to have corporate commitments or plans to participate in the vehicle integration of methanol- or gasoline-powered automotive fuel cell engines.

Daimler-Benz is the leader in the integration of PEM fuel cell power plants into bus, van and automobile platforms. This leadership was established through development and on-road demonstration of the NeCar 1 and 2 hydrogen-air fuel cell vehicles and extended to the NeCar 3 methanol-air fuel cell experimental vehicle. The level of fuel cell subsystem physical integration achieved in NeCar 3 is shown in Figure III-4.

Key characteristics of NeCar 3 are summarized in Table III-14.

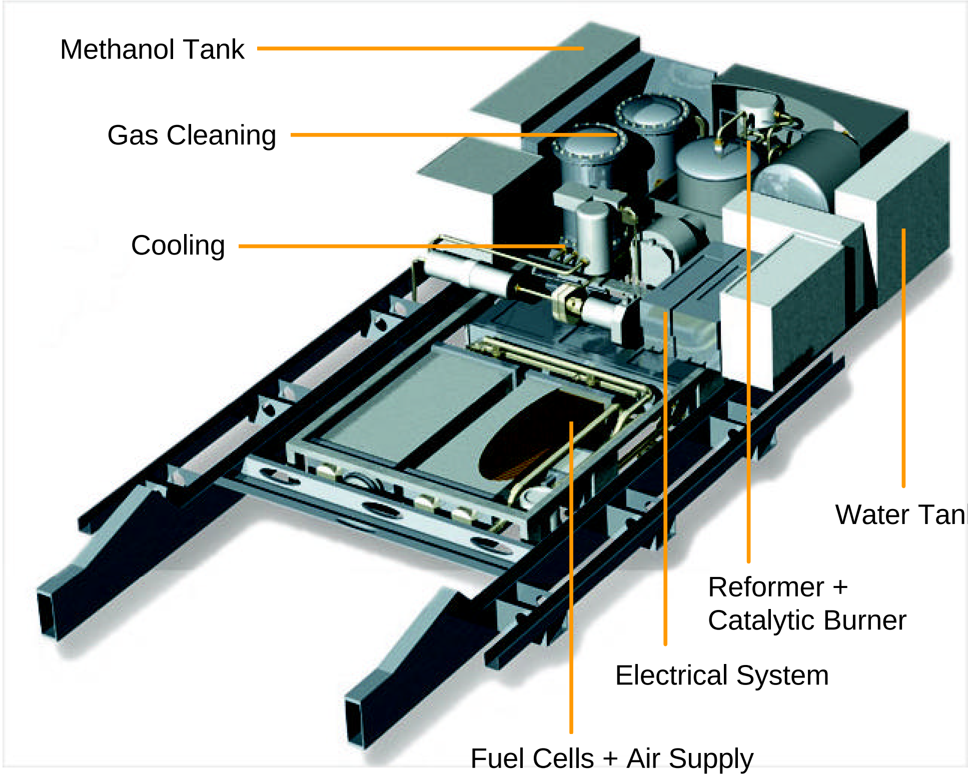


Figure III-4. Daimler-Benz NeCar 3 Methanol Fuel Cell Experimental Engine

Table III-14. Characteristics of Daimler-Benz NeCar 3 Methanol Fuel Cell Vehicle

Fuel Cell System	Power Density	0.054 kW/liter 0.066 kW/kg
	Voltage Range	185-280 V
Fuel Tank	Volume	38 liter
Vehicle	Rated Power	33 kW (continuous)
	Range	400 km
	Gross Vehicle Weight	1750 kg

NeCar 3 is a rolling test bed rather than a prototype vehicle. While its fuel cell system contains all functional components of a fuel cell engine, many/most of them are not yet in the form in which they are expected to be mass-manufactured. Nevertheless, system behavior is representative with the exception of the still rather long period required for cold start, and the vehicle has already been driven on public roads. Operated on a dynamometer over a standard Federal urban/suburban cycle but excluding cold start, it has yielded the first emission data for a methanol fuel cell automobile which confirm the expectations of zero NO_x and CO emissions and extremely low emissions of total hydrocarbons (see Section III.1.B).

The system integration efforts at Daimler-Benz are now focusing on the incorporation of advanced-technology, mass-manufacturable components and subsystems into complete fuel cell engines that will meet the packaging and weight constraints as well as the operability criteria of a production vehicle. Given the capabilities and resources of Daimler Benz and its key partners including Ballard, Ford and a number of other industrial organizations, it seems likely to the Panel that these efforts will succeed although the schedule for achievement of key milestones appears quite aggressive. At this time, the major uncertainties and risks are whether component/subsystem developments for manufacturability and the required manufacturing processes will produce a fuel cell electric engine technology that can achieve competitive cost when mass manufactured.

Japan

The major Japanese automobile manufacturers all are engaged in the exploration and development of PEM automotive fuel cells although to different degrees (see Sections III.1.A and B). Honda has a strong R&D program in PEM stack technology, Mitsubishi is developing an advanced methanol processor and a small PEM stack, and Nissan has evaluated the efficiency and environmental potential of fuel cell vehicles before engaging in R&D which appears to focus on the uncertain but intriguing potential of the direct methanol fuel cell.

Toyota appears to be the only Japanese car maker that is pursuing systems integration at this time. Toyota's current efforts and status in technology development and system integration are difficult to evaluate on the basis of the limited information given to the Panel. However, Toyota very likely invested significant efforts in developing the PEM hydrogen-air fuel cell and hydrogen alloy storage technologies and their integration into fuel cell-battery hybrid vehicles that demonstrated the technical feasibility of the concept. This effort no doubt benefited from Toyota's leadership in hybrid vehicle technology.

In October 1997, Toyota presented the concept of the company's "FCEV," a methanol fuel cell vehicle based on the platform of the 5-door RAV4 and using the RAV4 EV electric drivetrain. A diagram of the FCEV's hybrid power system configuration is shown in Figure III-5; key vehicle characteristics are summarized in Table III-15.

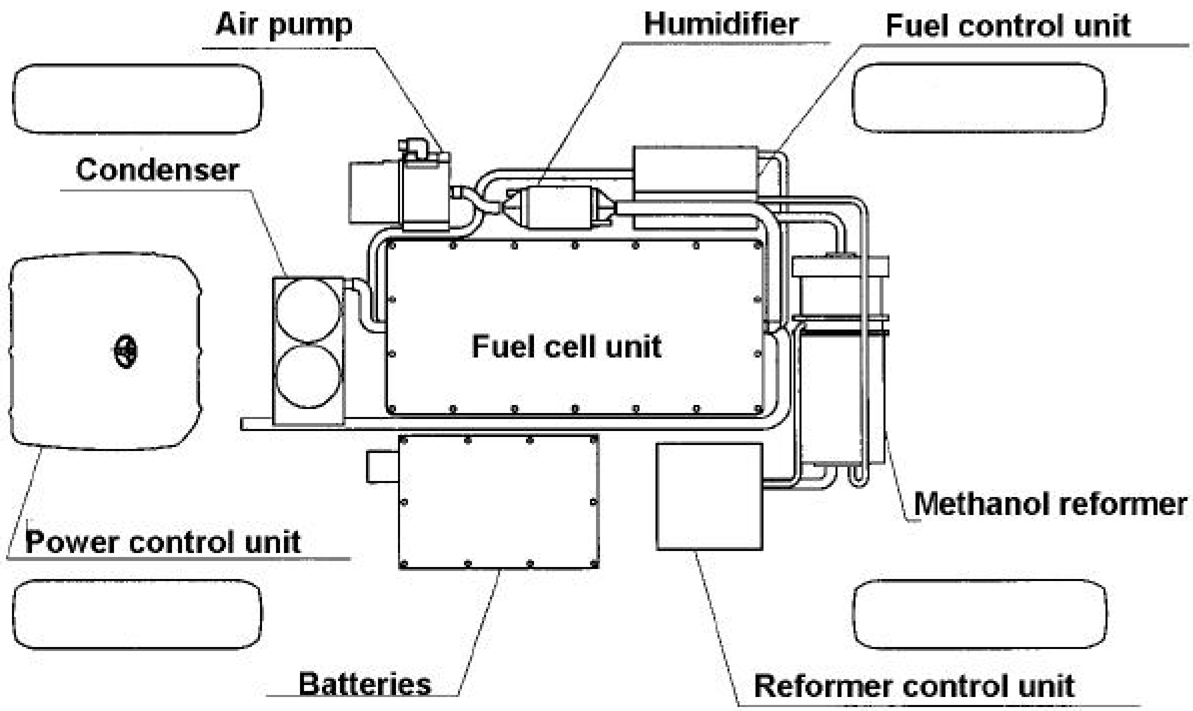


Figure III-5. Diagram of Toyota's Fuel Cell-Battery Hybrid Electric Engine

Table III-15. Specifications of Toyota's FCEV Fuel Cell Electric Vehicle

Performance	Maximum speed	125 km/hr
	Range on full tank	500 km
Drive	Type	Front motor, front wheel drive
Drive motor	Type	Permanent magnet, synchronous
	Maximum power	50 kW
	Maximum torque	190 Nm
Fuel cell	Type	Polymer electrolyte
	Length/Width/Height (mm)	1,080/500/240
	Rated output	25 kW
Methanol reformer	Diameter/length (mm)	300/600
Fuel		Methanol

Figure III-5 suggests a high degree of subsystem development and physical integration. If Toyota's vehicle (a mock-up of which was exhibited at the 1997 Frankfurt Motor Show) (1) actually conforms to the configuration shown in Figure III-5, (2) exhibits a high degree of functional integration, and (3) demonstrates good operability and efficiency, Toyota will have established one of the leadership positions in methanol fuel cell electric engine technology and systems integration.

Summary and Outlook, System Integration

In summary, increasing efforts are now being devoted to the difficult task of integrating PEM fuel cell components and subsystems into fuel cell power plants and, in turn, integrating power plants physically and functionally into fuel cell electric vehicles. Most of these efforts are still in the early stages, with focus on defining and resolving the most critical integration issues including (1) integrated operation of fuel cell stack and fuel processor, (2) reducing fuel processor weight and volume, and (3) integrated operation of the entire fuel cell engine including all of its thermal and water management functions.

The leading effort(s) have successfully demonstrated breadboard-level subsystem and vehicle system integration, and they are now focusing on integrating mass manufacturable component and subsystem technologies into increasingly packaged and prototypical fuel cell engines.

E. COST CONSIDERATIONS

Less than 5 years ago, the prospects for fuel cells as automobile engines seemed rather remote because PEM fuel cell stacks had low power density, and suitable fuel processing technology did not exist. No doubt specific costs (e.g., in $/kW) would have been very high even if this early technology had been mass-manufactured. Appropriately, however, R&D was more concerned with achieving the major performance increases required before automobile applications could seriously be considered.

Since then, and as discussed in the preceding sections, impressive advances have brought PEM fuel cell stack technology to the required performance level, the development of fuel processors has reached the breadboard stage, and a few developers have achieved functional integration of subsystems into experimental fuel cell power plants. The leading programs are now developing fuel cell components and subsystems that have potential for being mass-manufactured at low cost, bringing into sharp focus the extremely low cost target for competitive automotive fuel cell power plants.

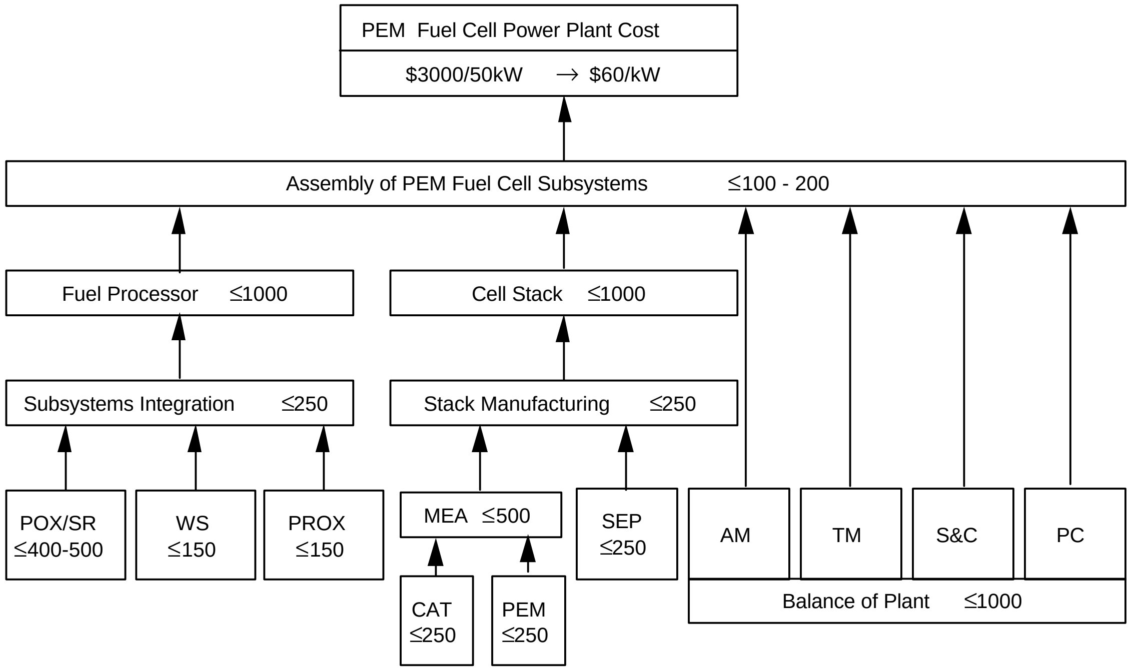
Figure III-5 shows a representative PEM fuel cell engine cost target[4] for a 50 kW PEM fuel cell power plant, and it illustrates how this cost can be broken down into a hierarchical scheme of targets for the cost of the most important materials, components, subsystems, and the generic manufacturing/assembly operations involved in producing the power plant. In the following sections, the prospects for achieving some of the most critical cost targets are discussed on the basis of information obtained or estimated by the Panel.

PEM Fuel Cell Stacks

The PEM fuel cell stack cost target of ≤\$1000/50kW (≤\$20/kW) appears achievable on the basis of the stack component costs projections obtained from selected developers or made by the Panel (see Section III.1.A). Specifically, at light loadings (e.g., 0.1 mg per cm^2 for each side of an electrode), catalysts will contribute \$100-150 to the cost of the MEAs used in the stack; this calculation assumes a cell-level performance of $1W/cm^2$. With the same performance assumption and a cost projection of \$20-50 per m^2 (a 10-30 fold reduction from today's cost of Nafion-type membranes, see Section III.1.A) , membranes will contribute \$100-250. Adding an estimated MEA manufacturing cost of \$100 (\$2/kW) brings the cost of (mass manufactured) MEAs to about \$300-500 for the 50kW stack. The cost of the bipolar separator plate must be reduced by an order of magnitude from today's level. As discussed in Section III.1.A, several promising approaches to cost reduction are being pursued, with emphasis on low-cost materials and manufacturing methods. Developers appear optimistic about the prospects to reduce separator costs to ≤\$1 per plate which corresponds to \$200-300 per stack, depending on the cell area and the number of cells used in the stack.

A cost of less than \$5/kW for stack assembly (≤\$250 for the 50kW stack, see Figure III-6) is considered achievable in fully automated production because the hardware required (tie bolts, compression plates, etc.) is low cost. Adding up all these cost contributions results in the projection of approximately \$750-1000, suggesting that the ≤\$1000 cost target for the 50 kW stack can be met albeit only if every important component and the stacks themselves are produced in automated mass manufacturing operations.

[4] The \$60/kW target (\$3000 for a complete 50kW power plant) in Figure III-6 is close to the PNGV program goal (see Table II-4) for year-2004 mass manufactured PEM fuel cell power plant technology. Some automobile manufacturers argue that economic parity with conventional IC engines requires fuel cell power plants to meet even lower cost goals, but there is no universally accepted number. Because fuel cell power plants are expected to have operating cost advantages due to higher efficiency, they may not have to match IC engine costs for economic parity. Moreover, increasingly stringent emission control and efficiency standards may well result in higher cost of future ICEs and/or credits for fuel cell electric engines. In view of these uncertainties, the Panel considers \$60/kW a reasonable upper limit for the cost of automotive fuel cell power plants.



POX/SR	Partial Oxidizer/Steam Reformer	SEP	Separator Plates
WS	Watergas Shift Reactor	AM	Air Management Subsystem
PROX	Preferential CO Oxidizer	TM	Thermal Management Components
MEA	Membrane-Electrode Assembly	S&C	Sensors and Controls
CAT	Anode and Cathode Catalysts	PC	Power Conditioner
PEM	Proton Exchange Membrane		

Figure III-6. Approximate Cost Goals Breakdown for PEM Fuel Cell Electric Engine

<u>Fuel Processor</u>

While the bases for projecting the costs of PEM automotive fuel cell stacks are specific and appear to be adequately supported, the Panel was unable to obtain data on which to base confident cost projections for fuel processors[5]. Current reactors and their assemblies into fuel processor “breadboards” are laboratory devices or experimental units, constructed without consideration of cost; even in the leading programs, they have not yet reached the preprototype stage.

[5] The very high costs of the natural gas fuel processors for the phosphoric acid fuel cell systems being commercialized in small numbers for electric power generation do not provide a basis for projecting the costs of automotive technology. They do make clear, however, that fully automated mass manufacturing will be essential for acceptable fuel processor cost.

The Panel believes, therefore, that available projections of fuel processor costs need to be viewed with caution. One such projection, made in 1994 by GM under DOE contract, indicated a processor cost of $1077/60kWe. More recently and as noted in Section III.1.B. ADL projected $16-25/kWe, or about $800-1250 for a 50kWe processor. While these projections suggest that the <$1000 target given in Figure III-6 is achievable, more confident projections must await development of designs capable of meeting all functional requirements for the fuel cell engine application and being mass manufacturable at very low cost.

Balance of Plant

As discussed in Section II.2.D and shown in Figures II-6 and II-7, a fuel cell electric engine has numerous components beyond the two major functional subsystems (stack and fuel processor) all of which contribute to engine cost. Probably the largest fuel cell BoP cost items are the computer-based control system and the power conditioner. The main part of the air handling system (the compressor-expander-drive motor assembly) is another high-cost BoP item. As suggested in Figure III-6, these three major items (plus all the smaller components) together should cost less than $1,000 for a 50kW fuel cell electric engine, or less than $20/kW.

The difficulty to meet this cost target can be appreciated when considering that not many years ago power conditioners alone cost $50-100/kW in larger capacities albeit produced in relatively small numbers. Similarly, the turbocompressors and turbochargers in today's commercial equipment cost far more than the fraction of $50/kW that can be allocated to the air handling system (see Figure III-6). There is as yet little understanding to which level air management subsystem costs might eventually be reduced; the contracts awarded by DOE in 1996-7 for development of 50kW turbocompressors contain performance targets only.

The Panel was given little specific information on BoP costs projected or targeted by fuel cell electric engine developers. At present these developers focus quite appropriately on the resolution of the technical and cost issues surrounding development and prospective manufacturing of the major fuel cell subsystems and their integration into functional electric engines. There is little evidence that the technical bases for achieving very low BoP costs are being established by the developers and/or their suppliers. Automobile manufacturers appear to believe that all BoP cost issues will eventually yield to their broadbased experience and capabilities for very low cost mass manufacturing of mechanical, electric and electronic technology.

Summary and Outlook, Costs

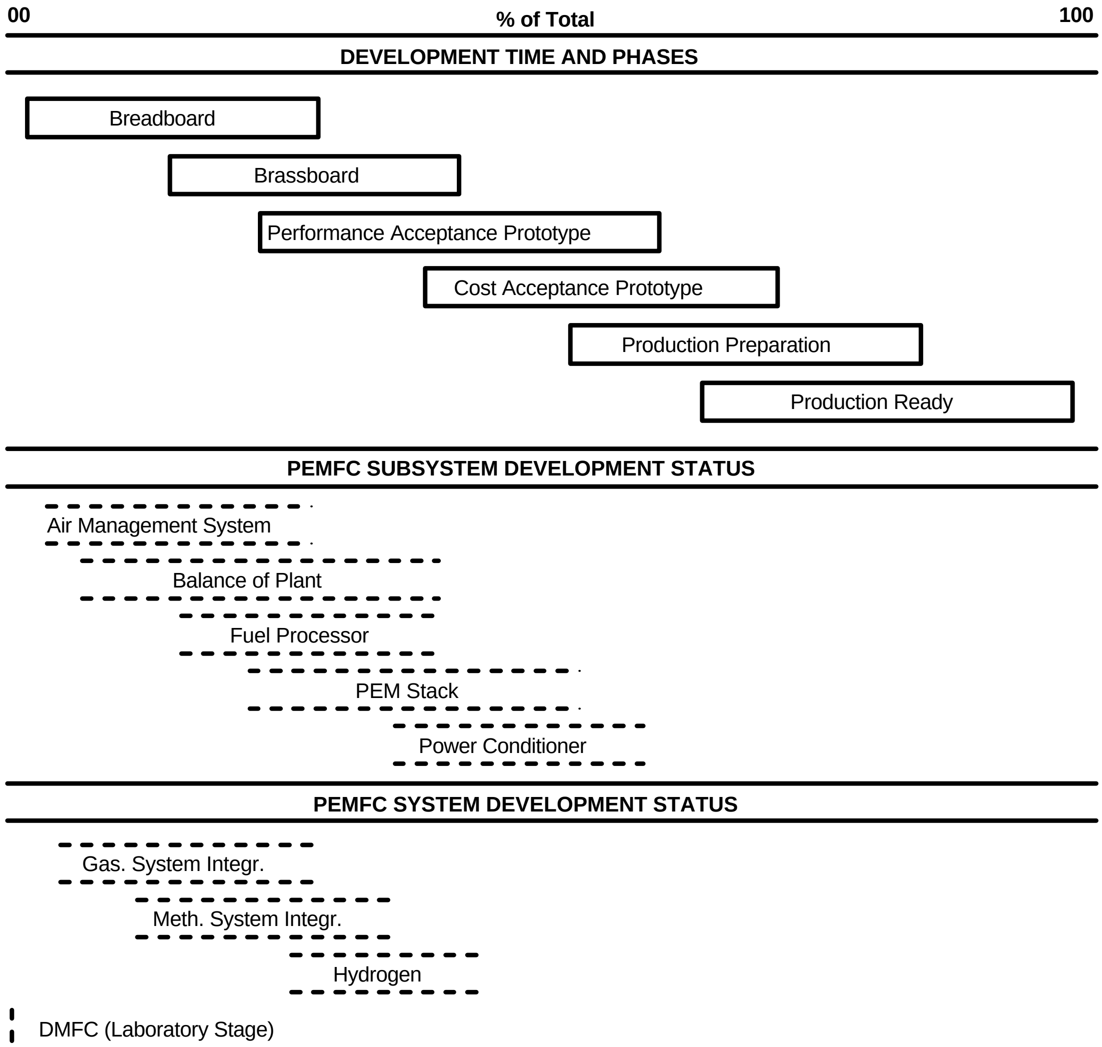
In summary, on the basis of the performance already achieved with preprototype stacks, there appear to be reasonable prospects for meeting the \$20/kW (\$1000/50kW) cost target for automotive PEM fuel cell stacks if production volume reaches about 100,000 - 200,000 units per year. At this level, the most critical stack components — membrane, MEA and separator plate — will reach production volumes that justify true mass manufacturing methods and that should permit achievement of component costs close to the targets in Figure III-6.

The cost picture is far less clear for methanol and gasoline fuel processors. With the exception of a small amount of platinum catalyst needed for selective oxidation of CO to acceptably low levels, the fuel processing subsystem does not contain inherently expensive materials. However, this subsystem is quite complex since it consists of a number of functionally separate units that need to be closely integrated with respect to the flows of processed fuel and heat. A few estimates have been made for the cost of mass manufacturing fuel processor components and the integrated subsystem, but these are not based on fully engineered, mass-manufacturable technology. In particular, since today's experimental fuel processors generally do not yet meet the rapid start-up criteria, current designs may not provide an adequate basis for materials and manufacturing cost estimates. In this situation, perhaps the most encouraging prospect for acceptable fuel processor costs is that major commitments are being made by a number of highly competent organizations (see Table III-8) to develop this key subsystem for automotive applications.

Balance of plant equipment — including in particular the turbocompressor-based air management subsystem; fuel cell power plant subsystem and system controls; and the power conditioner — also present severe cost challenges that need to be addressed very soon to avoid possible "show stoppers." The capabilities and resources of automobile manufacturers to develop and implement low cost mass manufacturing processes will be essential for meeting these challenges.

The Status of PEM Automotive Fuel Cell Technology: Summary

Clearly, then, the efforts of the past 5-10 years have moved PEM fuel cells from infeasibility to candidacy as automotive power sources; no longer do there appear to be fundamental barriers to achieving the required characteristics. However, as discussed in the preceding sections, PEM automotive fuel cell power plants — and their integration into complete engines — have not yet reached the levels of technological, system and manufacturing development required for a confident prediction that fuel cell power plants will become competitive with internal combustion engines. In particular, it is difficult to ascertain from the present status when — or, indeed, whether — acceptable operating characteristics and cost targets can be achieved. Open questions about choice and availability of fuels suitable for PEM fuel cell electric engines add to this uncertainty. The Panel's view of the current status of PEM fuel cell subsystem and system development is summarized graphically in Figure III-7.



The development timeline in this figure is "calibrated" not in years but in percentages of the total development time (from breadboard to production-ready technology). The total time will be different for different fuel cell subsystems, with shorter times (e.g., 2-4 years) for less complex components/subsystems and perhaps 10 years for complex subsystems like the fuel processor and for complete fuel cell engines.

Figure III-7. PEM Automotive Fuel Cell Technology: Development Timeline and Status

A series of difficult technical and cost challenges remain. To move automotive fuel cell technology through the phases sketched in Figure III-7 will require major development and engineering efforts in an exceptionally wide yet integral range of technical areas. The ultimate success in developing and establishing PEM fuel cell power plants as automotive engines will depend heavily on the technical and financial resources committed to these efforts over the next several years, and it will be impacted importantly by the choice of fuel(s) made in the leading programs. Fuel choice and the associated issues are discussed in Section III.2. The programs and resource commitments of key organizations — PEM fuel cell engine developers, automobile manufacturers engaged in PEM fuel cell engine development , and government agencies supporting R&D on limiting problems and enabling technologies — are reviewed in Section III.3.

F. THE DIRECT METHANOL FUEL CELL (DMFC)

The discussions in Sections III.1.B-E make clear that the development of automotive fuel cells would be greatly simplified — and the prospects for acceptable levels of complexity and costs of fuel cell engines materially enhanced — if the fuel could be used in the PEM fuel cell stack directly, without prior chemical processing. Hydrogen is much preferred from this standpoint but its storage and cost present difficult issues as reviewed in Section III.2.A below.

Among today's practical fuels, only methanol has sufficient electrochemical reactivity to be a candidate for direct use, but the issues discussed in Section II.2.A — low performance and crossover of methanol — have kept the DMFC from practical applications up to now. A new approach pioneered at the Jet Propulsion Laboratory (JPL) has resulted in significant performance improvements, and this approach now has been taken up by other organizations including the Los Alamos National Laboratory (LANL) and no doubt several of the major automotive fuel cell developers. To gauge technical progress and prospects of the DMFC, the Panel visited JPL early in its investigation and updated its observations in recent months with new information from JPL, LANL and other organizations. The Panel's main findings are summarized here.

In a major departure from the past, JPL's method is to feed methanol as an aqueous solution rather than as vapor to the membrane-electrode assembly. Somewhat unexpectedly, JPL's method results in much higher anode performance and reduced need for platinum electrocatalyst compared to previous DMFC work. Representative of current laboratory DMFC performance is a current density of 300 mA/cm^2 at 0.5 V cell voltage and 90°C, for a power (area) density of 0.15 W/cm^2; this encouraging result is about 20% of the power density achieved with high-performance PEM-based hydrogen anodes. The best anode and cathode electrocatalysts appear to be platinum-ruthenium alloys which are less sensitive than pure platinum to poisoning by the carbon monoxide that is formed as an intermediate product of methanol electrochemical oxidation at both electrodes. At present, JPL requires about 6.5 milligrams of alloy per cm^2 of cell for good, stable performance.

The efficiency of this cell is currently below 35% since substantial methanol crossover occurs also in JPL's cell operating method. As a consequence, research is being undertaken in several laboratories to discover membranes that combine the excellent stability and good proton conductivity of Nafion-type materials with greater resistance to methanol permeation. New membranes (including non-fluorinated materials) are being tested but the Panel is unaware of any breakthroughs in this area.

Researchers at LANL have achieved comparable performance with 2.5 mg catalyst per cm^2 of cell by increasing cell temperature to 100°C. Operating hydrogen-air PEM fuel cells at 100°C and above can be problematic because Nafion-type membranes are more easily dehydrated and damaged as cell temperature increases. In the DMFC, intimate contact of membranes with the aqueous methanol solution promotes good hydration, with stable performance at 100°C for ≥2000 hours observed at LANL. Because methanol reactivity increases more rapidly with temperature than does its diffusion through Nafion-type membranes, cell efficiency under typical operating conditions can be somewhat higher at higher temperatures, for example around 37% at 100°C.

Verifyable engineering designs and cost estimates for direct methanol fuel cells, stacks and balance-of-plant equipment are not yet available. Consequently, it is difficult to assess the technoeconomic prospects of the DMFC for automobile propulsion. However, a comparison of the basic performance data above with those for hydrogen-air (H-A) PEM cell technology permits at least a "snapshot" evaluation of the current prospects of the DMFC and an indication of the improvements needed to make the concept competitive.

With this caveat, consider that (1) the (area) power density of the DMFC is at best 20% of hydrogen-air cells and (2) the DMFC catalyst loading per unit area is approximately 10 times larger. From (1) follows that based on present cell performance, a DMFC stack would cost 5 times more than a H-A stack of the same power rating[6] — if the amount of catalyst per kW of output were the same. Actually, that amount is 50 times larger for the DMFC which at present has about five times less power and 10 times more catalyst per unit area. Referring now to the H-A component and stack cost estimates in Section III.1.E above, a 50 kW DMFC engine

[6] This assumes that the key components and design parameters — such as membranes, separator plates, current collectors, single cell thickness, etc. — of DMFC and H-A PEM stack technology will be quite similar, a reasonable assumption at the present state of development.

would, therefore, cost about $5,000 for the basic stack plus at least $5,000[7] for the extra catalyst, for a total of $\geq$\$10,000, almost 3 times higher than the upper limit for a cost-competitive fuel cell engine.

Clearly, major advances in methanol anode performance — both, on a per-unit-area and a per-unit-weight-of-catalyst basis — are needed before the DMFC can be considered a good candidate for the development of fuel cell engines for automobiles. In the nearer term, such advances are more likely to come from research on electrocatalysts — advanced alloys, catalyst supports and electrode structures that achieve the highest possible specific activities and materials utilization — than through engineering development of stacks.

The methanol crossover problem also remains a major challenge. It is noted here that the observed losses of methanol (about 25% to 30%) refer to the situation at high current densities. Because the crossover rate depends on methanol concentration rather than cell current density, losses at low loads can be substantially higher unless the methanol concentration is adjusted instantaneously in proportion to the load. Here, the goal must be the exploration and discovery of new membrane materials that have high conductivity for protons while presenting an effective barrier to methanol crossover. It will be very important that such membranes can operate stably at higher temperatures (e.g., 150°C or above) where the direct methanol reaction is sufficiently rapid to support the high current densities needed for automotive applications.

In summary, despite the impressive progress made recently, the direct methanol fuel cell is still in the laboratory research stage with respect to its most critical issues. Because of the fundamental attractiveness of the DMFC concept, many if not most fuel cell developers and major automobile manufacturers are supporting DMFC programs. Consistent with the Panel’s assessment, these are research programs, funded at a small fraction of the total PEM fuel cell development effort modest and largely focused on the issues discussed above. DMFC engines for automobiles are unlikely to emerge from these efforts during the next 10 years.

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[7] Catalyst costs for 50 kW H-A stack are estimated to be $100-$250, see Section III.1.E; 50x ($100-$250) = $5000 to $12,500.